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Reports
Kauffman,
J.B.

Quantification of Carbon Dynamics...
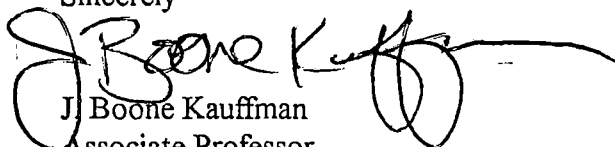
DEPARTMENT OF
FISHERIES AND WILDLIFE

15 November 1995
Dr. Darold Ward
USDA Forest Service
Intermountian Fire Sciences Laboratory
PO 8089
Missoula MT 59807

Dear Darold

I am very pleased to present my final report for Amendment INT-93834
Quantification of Carbon dynamics, forest biomass, nutrient pools and
consumption by fire in Amazonian and Cerrado ecosystems. The report is
divided into three parts. Part 1 is the results of extensive analysis of biomass and
nutrient pools and fire effects in the Brazilian Cerrado. Part 2 includes the
biomass and fuel consumption of all fires quantified thus far in the tropical forests
of Brazil. Part 3. Is a specific and detailed analysis of biomass, nutrient pools,
and fire effects in converted cattle pastures in the Brazilian Amazon.

Much of this report will soon be submitted for publication in the refereed
literature. This includes submissions to Oecologia, and Oikos, two
internationally renowned journals of ecology. If you desire ant additional
information please do not hesitate to contact me. As always it is a pleasure to
have had the opportunity to collaborate with you.

Sincerely

J Boone Kauffman
Associate Professor

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QUANTIFICATION OF CARBON DYNAMICS, FOREST BIOMASS, NUTRIENT POOLS, AND CONSUMPTION BY FIRE IN AMAZONIAN AND CERRADO ECOSYSTEMS

Amendment INT-93834
A Final Report Presented to:
Intermountain Research Sation
USDA Forest Service
324 25th Street
Ogden Utah 84401

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Department of Fisheries and Wildlife
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14 November 1995

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CHAPTER 1
INTRODUCTION

Tropical savannas are distributed between the Tropic of Cancer and the Tropic of Capricorn in Central America, South America, Africa, South Asia, and Australia. Savannas cover approximately 13 % of the terrestrial land surface (Bolin et al. 1993). They are characterized by pronounced dry and wet seasons, a distinct structure comprised of grass and tree layers, and the presence of frequent fires (Bourlière 1983). In South America, tropical savannas occupy 250 million ha. Brazil contains 80 % of South American savannas, followed by Colombia with 8% and Venezuela with 5% (Fisher et al. 1994). The other 7 % is found in Bolivia, Surinam and Guyanas. In Venezuela and Colombia, tropical savannas are referred to as Llanos (Blydenstein 1962 1967, Silva et al. 1971, Sarmiento 1983), while Cerrado is the commonly used term in Brazil (Goodland 1971, Coutinho 1976, Eiten 1978, Sarmiento1983, Kauffman et al. 1994).

Cerrado *sensu lato* (s.l.), or simply Cerrado includes plant communities of different compositions and structures, varying from grassland to forest (Eiten 1972) (Figure 1.1.). It has been classified by physiognomy (Eiten 1972, Coutinho 1976), and quantified in terms of tree density, height and basal area (Goodland 1971). The most common vegetation communities defined and classified by these authors are:

campo limpo: a pure grassland nd totally absent of trees. The flora here is often similar to the surface layer of woodland community types. In the bottom part of valleys, campo limpo usually has a shortage of water in the dry season and an excess of water during the rainy season
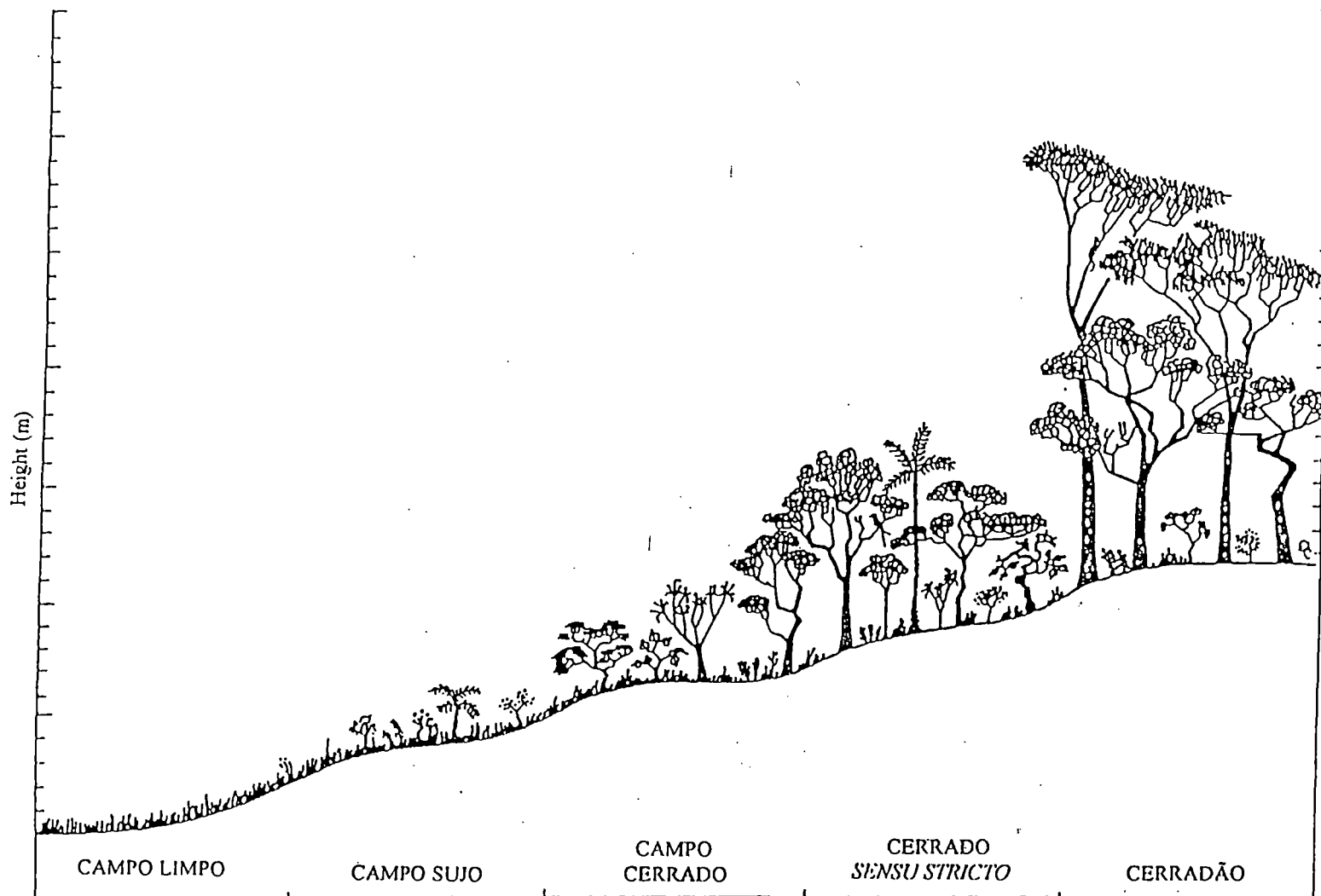
Figure 1.1 Cerrado *sensu lato* vegetation gradient (Courtesy: Dian Cummings).

The y-axis is labeled "Height (m)". The vegetation gradient is divided into the following zones from left to right: CAMPO LIMPO, CAMPO SUJO, CAMPO CERRADO, CERRADO *SENSU STRICTO*, CERRADÃO.

campo sujo: a grassland with few scattered shrubs, and acaulescent palms. Woody plants in this community may reach 3.0 m. Tree density is less than 1000 ha^{-1}, and total basal area is 3 m^2 ha^{-1};

campo cerrado: an open savanna/woodland. Overstory cover is < 30-40 %. Trees and shrubs occur over a continuous layer of grasses and herbs. Average tree height is 4 m, tree density is 1400 ha^{-1}, and total basal area is 7.6 m^2 ha^{-1};

cerrado sensu stricto (s.s.): a tree-dominated plant community with an overstory covering 30-40 %. Grass and herbs are also found in this community. Mean tree height is 6 m. Tree density is approximately 2000 ha^{-1}, and total basal area is 16.8 m^2 ha^{-1};

cerradão: a medium-tall arboreal form with a closed or semi-closed canopy. In general, grasses, herbs and shrubs are sparse or absent. Canopy cover can be more than 50 %. Height of trees is 9 m and tree density is 3000 trees ha^{-1}. Total basal area is 30.0 m^2 ha^{-1}.

The Cerrado vegetation mosaic occupies 1.5 million km^2 in continuous area of the central part of Brazil. Patches of Cerrado s.l. are distributed in the Amazon tropical rain forest (the northern and western limits); in the Caatinga, a tropical dry forest (the eastern limit); and in the Pantanal, a wetland (the southwestern limit) (Coutinho 1990). The total Cerrado area covers approximately 1.8 million km^2 or 23 % of the Brazilian territory (Figure 1.2.). Cerrado s.s. is the most common community type, comprising 65 % of the total Cerrado s.l. area (Haridasan 1990). Campo cerrado, campo sujo, and campo limpo comprise together 12 %, and cerradão covers another 12 % (Adamoli and Azevedo 1983 cited in Adamoli et al. 1987). The remaining 11 % is distributed in riparian areas, mesophytic forests, and other small plant communities.

Climate has been suggested as the most influential factor contributing to the composition and formation of Cerrado s.l. (Eiten 1972, 1992). Precipitation ranges from 1300 to 1800 mm. The dry season extends from April to August and the wet season from September to March. Mean relative humidity varies from 38 to 96 %. Temperature, in

Figure 1.2. The distribution of Cerrado *sensu lato* vegetation in Brazil.

contrast is more constant throughout the year. The maximum average temperature is 25 °C and the minimum average temperature is 21 °C (Ab'Saber 1983). According to the Köppen classification (DNER 1976), Cerrado s.l. is AW climate type. Elevation is between 300 and 1700 m.

The majority of soils are Latosols, classified in the American soil taxonomy as Oxisols, and Ultisols. Soils are nutrient poor, dystrophic with low capacity of cation exchange, high concentration of aluminum, and pH varying from 4.0 to 5.0 (Eiten 1972, Lopes and Cox 1977, Adamoli et al. 1987, Haridasan, 1990). Soils are deep, with few differences in horizons, and colors varying from red to yellow. Soils are well drained, highly weathered and leached. Primary minerals are absent, and there is a predominance of oxides and hydroxides of iron and/or aluminum (Adamoli et al. 1987).

In addition to climate and soil conditions, fire has contributed to the vegetation composition and structure. Charcoal from the Cerrado is dated to 8600 years B.P. (Coutinho 1981). Records of indigenous populations using fire for hunting, war, and rituals are common (Magalhães 1913, Eiten 1975). The indigenous Kaiapos population still uses fire as a management tool to control snake and scorpion populations near settlements. Fire is applied just after the beginning of fruit formation of pequi (*Caryocar brasiliense* Cambess., Caryocaraceae) to insure that any pequi flower, a potential fruit, is not lost in fire consumption (Anderson and Posey 1987).

Plant adaptation to frequent fires is remarkable in this ecosystem. Basal and epicormic sprouts are common in trees and shrubs. Underground organs are common in the herbs, shrubs, and trees of Cerrado s.l. (Furley and Ratter 1988). Anomalous arrangement of meristematic tissues occur in palms, graminoids and velloziaceas (Rachid-Edwards 1956). Trees have a wide and high canopy and usually are not directly affected by fire. They also have a very thick trunk bark protecting the cambial meristematic tissues. Mortality of vegetation caused by fire is generally low and

insignificant (Ramos 1990). Fire return interval increases from grassland to woodland. However, fire rarely penetrates the cerradão forests (Eiten 1972, Goodland and Ferri 1979).

Grasses are predominantly from the C4 pathway, but C3 grasses tend to increase in the woody savannas (Filgueiras per. comm.). Ninety four percent of herbs are perennial (Warming and Ferri 1973, Coutinho 1978b). More than 700 woody species have being identified for all Cerrado s.l. Herbaceous and small shrubs species richness are approximately 127, and a total of 108 grasses and 54 orchids have been identified in the Cerrado (Heringer et al. 1977). Studies of plant community in Cerrado vegetation indicate a high beta diversity in cerrado s.s. flora (Ratter and Dargie 1992, Felfili and Silva Jr. 1993). Environmental factors, such as local fires, poor soil drainage, man-made disturbance (Gibbs et al.1983), soil fertility (Goodland and Pollard 1973), and topography (Oliveira-Filho et al. 1989) influence the distribution of communities within Cerrado s.l..

Similar to other tropical biomes, Cerrado s.l. is threatened by anthropogenic activities which may permanently alter plant composition, structure, productivity and overall biological diversity. The increasing of agriculture crops (e.g. soybeans, corn, and rice) results in deforestation of large areas of the Cerrado (Coutinho 1982). Moreover, the Cerrado is exploited to produce charcoal for steel companies (Felfili and Silva Jr. 1993). Urban settlements, dams, cultivated pastures, crop fields and degraded areas are estimated in 37 % of Cerrado area (Dias 1990). Projections for the year 2000 indicate that a total of 49 % of Cerrado land surface will be cleared for main crops, cultivated pastures and open areas (Nepstad et al. 1995). Only 1.5 % of the Cerrado is protected in the Brazilian park and reserves systems (Dias 1990).

Numerous studies of Cerrado vegetation ecology, and taxonomy have been carried out (Goodland and Ferri,1979, Filgueiras et al. 1993, Felfilli and Silva Jr.1993), there have been few studies of carbon and nutrient pools, or fire ecology (Coutinho, De Vuono, and Lousa 1978, Batmanian and Haridasan 1985, Kauffman et al. 1994).

Fire affects the vegetation, soil, fauna, nutrient cycling, alters energy flows and influences the atmosphere (Gillon 1983, Frost and Robertson 1985). Because of the great frequency and large areal extent of tropical savannas, fires in this ecosystem may contribute as much as one-third of all CO_2 arising from biomass burning sources (Crutzen and Andreae 1990).

The frequency, severity and size of fire are factors which define the fire regime in an ecosystem (Agee 1990). In Southern Africa, fire return interval of one to five years has been described (Huntley 1982; Trollope 1978, 1982). For campo limpo, estimations are one to two years and for campo cerrado three to five years (Eiten 1972, Coutinho 1979, Pivello and Coutinho 1992).

Fires in savannas are characterized as surface fires with a low flame height (Frost and Robertson 1985). Description of fire behavior is scarce for fires in Cerrado vegetation. Kauffman et al. (1994) determined the flame depth (1.7 to 9.7 m), flame angle (48° to 61°), flame length (2.7 to 5.4 m), flame height (1.8 to 3.7 m), rate of spread (1.4 to 30.0 m min. $^{-1}$), residence time (15 to 26 s), and fire line intensity (2842 to 16,394 kW m^{-1}) for fires in Cerrado communities near Brasilia, DF.

The quantities of nutrients released by fire depend upon factors, such as the quantity of biomass consumed, fireline intensity, the type of vegetation, and its concentration of nutrients in leaves, stems and other locations most susceptible to combustion (Frost and Robertson 1985, Coutinho 1990). Some nutrients are easily volatilized (e.g. N and S) while others are mostly deposited on the soil surface as ash or remain as residual material not consumed by fire (Frost and Robertson 1985, Kauffman et al. 1994). In Cerrado vegetation, nutrients such as Ca, K, P and Mg increase in availability in the upper 5 cm of soil following fire (Coutinho 1982, 1990). Inputs of nutrients from precipitation in campo cerrado in São Paulo state were recorded monthly by Coutinho (1979), who found that deposition is greater in the wet season when precipitation increases. However, there is also a contribution of nutrients via dry fall

during the dry season. In the same study area, Pivello and Coutinho (1992) reported great losses of N and S during fires. Near Brasilia, DF, the amount of N, C, and S lost by fire decreases along vegetation gradient from campo limpo to cerrado s.s.. In campo limpo most nutrients are lost by volatilization, but in cerrado s.s. the greater amount of nutrients are lost via particulate transport. For all communities, C, N, and S are the nutrients lost in the highest quantities (Kauffman et al. 1994).

The structure and arrangement of materials as well as moisture content are factors influencing levels of biomass consumption. Kauffman et al. (1994) quantified fuel loads in Cerrado vegetation at the IBGE Ecological Reserve. Fuels ranged from 7 Mg ha^{-1} in campo limpo to 10 Mg ha^{-1} in cerrado s.s. (tree biomass > 2.0 m in height was not included). These values are low when compared with slashed fuels in tropical dry forest (Caatinga, 74 Mg ha^{-1}) and tropical rain forest (290 to 435 Mg ha^{-1}) (Kauffman et al. 1993, 1994). Fuel biomass consumed by fire (the combustion factor) in Cerrado is 100 % in campo limpo, 97 % in campo sujo, 71 % in campo cerrado, and 84 % in cerrado s.s.(Kauffman et al. 1994). The combustion factor in tropical dry forest ranges from 74 to 88% and tropical primary slashed rain forest range from 42 to 57 % (Kauffman et al. 1993, 1995).

While a few studies of aboveground biomass exist, studies of root biomass in Cerrado vegetation are nonexistent. However, individual root systems of species have been classified into deep, medium or surface depth classes (Rawithscher 1948). Subterranean organs were described by Rizzini and Heringer (1961, 1962).

Root systems in African savannas are well developed, and penetrate deeply into the soil. However, the majority of belowground biomass is located in the upper 30 cm of the soil surface. In addition, the root systems of herbaceous and woody plants are greater in biomass than aerial parts (Menaut and Cesar 1979). Shrubs and trees are characterized as having a tap-root with well developed lateral roots (Hopkins 1962). Mean root biomass in the forest-savanna mosaic in Lamto, Ivory Coast, varies from 10.1 to 10.0

Mg ha^{-1} in contrast to aboveground biomass which range from 3.3 to 4.4 Mg ha^{-1} (Lamotte 1978). In South America, Sarmiento and Vera (1979) determined that maximum root biomass range from 1.2 to 1.9 Mg ha^{-1} in an area of western Venezuela llanos.

Carbon nutrient concentration in Cerrado s.l. has been estimated in the range from 0.4 % to 4.6 %, while nitrogen concentration ranges from 0.04 to 0.23 % (Goodland and Ferri 1979), and sulfur supply is low (McClung and Freitas 1959). A carbon/nitrogen ratio of 11.2 has been reported for Cerrado s.l. of Mato Grosso state (Askew et al. 1970). Soil nutrient pool studies are scarce for Cerrado s.l. Kauffman et al. (1994) determined a range of 656 to 1,670 kg ha^{-1} for the soil nitrogen pool to a depth of 0.10 m in the gradient campo limpo to cerrado s.s.. Total ecosystem pool for any other tropical savanna has not been determined to date.

In order to understand the nutrient pools, structure, fire ecology and effects on Cerrado vegetation, three studies were undertaken. Objectives of these studies were to (a) quantify total aboveground biomass, fire behavior, and biomass consumption, (b) quantify the structure and total root biomass of plant communities, and (c) quantify ecosystem C, N, and S pools and dynamics along a vegetation gradient in the Brazilian Cerrado.

CHAPTER 2
TOTAL ABOVEGROUND BIOMASS, FIRE BEHAVIOR, AND BIOMASS CONSUMPTION ALONG A VEGETATION GRADIENT IN THE BRAZILIAN CERRADO

Abstract

Aboveground biomass, fire behavior and consumption were quantified in a Cerrado *sensu lato* (s.l.), vegetation gradient from grassland (campo limpo) to a woodland with closed shrub and more scattered trees (cerrado *sensu stricto*) in Brasilia, DF, Brazil. Total aboveground biomass increased from campo limpo (5,542 kg ha^{-1}) through campo sujo (9,344 kg ha^{-1}), cerrado aberto (24,847 kg ha^{-1}) and cerrado denso (24,944 kg ha^{-1}) (The latter two communities are variants of Cerrado *sensu stricto*). Components varied among communities, trees were non existent in campo limpo but had a biomass of 12,915 kg ha^{-1} in cerrado denso. Conversely, grasses declined along the gradient from 3,955 to 1,600 kg ha^{-1}. This variability influenced the fire behavior, consumption and subsequent plant recovery. Fireline intensity increased from campo limpo (557 kW m^{-1}) to cerrado denso (3,693 kW m^{-1}). Consumption in campo limpo and campo sujo was 95.6 % and 98.7 %, respectively. In cerrado aberto and cerrado denso, some shrub stems and trees remained after fire; consumption in these communities was 72.6 and 66.1 %, respectively.

Total biomass in Cerrado *sensu lato* (s.l.) had not been previously measured. The results of this study indicate that compared to other Brazilian tropical ecosystems such as, tropical dry forest and tropical rain forest, Cerrado has the lowest aboveground biomass. However, biomass is high compared to other tropical savannas of the world.

Introduction

Cerrado *sensu lato* (s.l) ecosystem is a diverse tropical savanna with a vegetation

gradient ranging from pure grassland (campo limpo) through grassland with small and

sparse shrubs (campo sujo), an open savanna/woodland (campo cerrado), savanna

woodland dominated by shrubs and trees (cerrado *sensu stricto*), and a closed canopy

forest (cerradao) (Coutinho 1976). This ecosystem comprises 1.8 million km^2 in the

central part of Brazil (Ab'Saber 1983). Execed in size only by the Brazilian Amazon

tropical forest (Furley and Ratter 1988). It is characterized by distinct tropical wet and

dry seasons, classified as AW by Köppen (Sarmiento 1983, DNER 1976), and by a

constant temperature through the year. Soils are deep, well drained, and low in mineral

nutrient concentration and pH. They have a low base saturation and a high concentration

of aluminum (Eiten 1972). Climate and soil conditions combined with frequent fires

have been suggested as determinants of Cerrado s.l. vegetation in Brazil (Eiten 1972,

Coutinho 1990).

Fire has been an ecosystem disturbance in the Cerrado for millennia (Eiten 1972,

1975). The oldest recorded charcoal is dated at 8600 years B.P. (Coutinho 1981). Berger

and Libby (1966) found charcoal pieces near Brasilia, DF dated about 1600 years B.P.

Indigenous people of the Cerrado had many traditional uses for fire such as for hunting,

agricultural purposes, myths, festivals and war (Magalhães 1913, Eiten 1975, Coutinho

1982). Currently, fire is used as a management tool for increasing vigor of pasture

grasses for livestock, deforestation and clearing of large areas for agricultural purpose,

pest control, and may also occur accidentally (Goedert 1983, Coutinho 1992). The

majority of fires occur at the end of the dry season. Principal ignition sources are humans

and more rarely lighting (Coutinho 1990).

The structure, physiognomy, and floristic composition of this ecosystem appears

to be well-adapted to or even dependent upon fire (Coutinho 1982). Graminoids provide

a combustible fuel source and are well represented in Cerrado vegetation types. Following fires, graminoids recover rapidly because their basal meristems are protected by green leaf sheaths, or soils (Rachid-Edwards 1956). In addition to plants of Poaceae and Cyperaceae, Bouillenne (cited by Rachid-Edwards, 1956) reported similar adaptive traits for plants of the Velloziaceae, and Bromeliaceae, which are common families in Cerrado s.l.. Shrubs and perennial herbs have the capacity to sprout from subterranean tissues, even if all aboveground biomass is consumed by fire (Eiten 1972). Trees have thick bark to protect their cambial tissues (Eiten 1975) from thermal damage (Coutinho 1990). Some trees such as *Aspidosperma tomentosum* Mart. (Apocinaceae) have dormant apical buds that are protected by dense and hairy leaves (Coutinho, 1990). If those apical buds are killed by fire, adventitious buds may produce epicormic sprout. The occurrence of a long dry season and low relative humidity in combination with these biological and ecological traits result in an ecosystem very susceptible yet adapted to fire.

The fire return interval has been determined to be as frequent as once a year in grasslands (Eiten 1972), and three years for campo cerrado (Pivello and Coutinho 1992). Eiten (1975) estimated the average frequency of fire set by indigenous people of the Cerrado area, Mato Grosso, Brazil, to be three to five years.

Few studies in Cerrado vegetation quantified biomass, or described fire behavior. Biomass of herbaceous layer was quantified by Cesar (1980) and Cavalcanti (1978) but components were not partitioned. gramineous and non-gramineous biomass of herbaceous layer of campo cerrado was determined (Batmanian 1983). Post fire biomass increases were investigated the following year in campo sujo (Rosa 1990). Comparison of biomass, fire behavior and effects of fire on consumption in Cerrado s.l. were reported by Kauffman et al. (1994), although trees were not included in their survey. Thus, total aboveground biomass (TAGB) in communities of Cerrado s.l. has not been described. Vegetation biomass may contain a great amount of stored C; deforestation and burning promote loss of this C to the atmosphere. Therefore, quantification of TAGB and

biomass consumption by fire is of great importance to understand C dynamics, and its contribution to the increase in CO_2 in the atmosphere.

Objectives of this chapter were to (1) quantify total aboveground biomass before fire, in a gradient from open grassland to a dense woodland; (2) partition the biomass into meaningful components in each community type based on plant morphology, ecosystem structure and influences on fire behavior; (3) describe fire behavior in each community; and (4) determine post fire biomass and biomass consumption by fire.

Study Site

The research was conducted at the Reserva Ecológica do Instituto Brasileiro de Geografia e Estatistica (IBGE Ecological Reserve) and at the Estação Ecológica do Jardim Botânico de Brasilia (JBB Ecological Reserve). They are located approximately 35 km south of Brasilia, DF, in Brazil (15° 51' S and 47° 63' W). The elevation is 1,100 m and slopes are < 10%. During the period from 1980 to 1992, mean annual temperature varied from 19.2 °C to 22.4 °C. Mean precipitation was 1482 mm distributed in two distinctive seasons; the wet season from October to March had 1257 mm and the dry season extended from April to September with 225 mm. Mean maximum relative humidity was 81% in December and the mean minimum was 55% in August (File data from Estação Agroclimatologica do IBGE 1980-1992).The IBGE and JBB Ecological Reserve vegetation is characterized by a mosaic of communities ranging from grassland to closed-canopy forest. At the IBGE Ecological Reserve 1,100 plant species distributed among 135 botanical families have been identified (IBGE internal publication). The most common families are Leguminosae, Asteraceae, Poaceae, and Orquidaceae; a number of rare species are present in the composition; endemism is common.

Among the fauna some animals such as, the giant ant eater (*Myrmecophaga tridactyla* Linnaeus), veado campeiro *(Ozotoceros bezoarticus* Hamilton-Smith*)*, and lobo guara (*Chrysocyon brachyurus* Ameghino*)* are in danger of extinction (IBGE internal publication, Alho 1990).

In this study, the biomass and structure of four community types was investigated, (campo limpo at IBGE Ecological Reserve and campo sujo, cerrado aberto and cerrado denso at the JBB Ecological Reserve). Cerrado aberto and cerrado denso are variant of cerrado *sensu stricto*. Cerrado aberto was characterized by a more open canopy cover compared to cerrado denso. Currently, the study areas are part of a biennial fire treatment in a study about fire effects on Cerrado vegetation.

Methods

Aboveground biomass was partitioned into components based upon plant morphology, influences on fire behavior, approaches necessary for the quantification of biomass. In each plant community, four clusters of six transects were established (Appendix 2.1.). Each transect was 15 m in length. Downed wood debris was quantified along all transects (n=24). Other components were measured in four transects in the same cluster. The first cluster was randomly established and the others were systematically set 50 m apart. Aluminum stakes marked each end of the transect to ensure their exact relocation after fire.

Downed wood debris

Downed wood debris was quantified in cerrado aberto and cerrado denso using the planar intersect method (Van Wagner 1968, Brown 1971, Brown and Roussopoulos 1974). This component was not present in the campo limpo and campo sujo grasslands. The planar intersect method consists of measuring all dead wood material that intercepts a transect. Diameter size classes were based upon the standard timelag classes described by Deeming et al. (1977). These classes are 0 to 0.64 cm in diameter (1-hr timelag fuels), 0.65 to 2.54 cm in diameter (10-hr timelag fuels), 2.55 to 7.6 cm in diameter(100-hr timelag fuels) and > 7.6 cm in diameter (1000-hr timelag fuels). The timelag constant is the time period required for a wood fuel particle within those diameter classes to lose 63% of its initial moisture content when placed in an equilibrium of standard laboratory conditions of 27 °C and 20% relative humidity (Pyne 1984). In this study, wood debris > 7.6 cm in diameter was not encountered in the communities surveyed. The 1-hr timelag fuels were inventoried along the first 5 m of the transect; 10-hr fuels were measured from 0 to 10 m, and the 100-hr fuels were measured along the entire 15 m transect. Biomass was calculated utilizing the following formula :

$$WD_{biomass} = \left(\frac{N*\pi^2*sec*d^2}{8*L} \right) * S$$

where:

$WD_{biomass}$ = Weight per unit area (g cm^{-2}),

N = Total number of wood debris intersections,

sec = Wood debris angle correction factor (degree) ,

S = Specific gravity (g cm^{-2}),

L = Length of sample plane (cm), and

d = Quadratic mean diameter (cm).

For each size class, a quadratic mean diameter, angle correction factors and specific gravity were based on data collected specifically for these communities (OSU file data). Slope correction factor in the original formula (not shown here) was not needed due to the level topography in all communities. After fire the transects were remeasured to quantify residual plant materials that were not consumed or deposited because of fire.

Herbaceous stratum, litter, and ash.

The herbaceous stratum contained hard wood litter, green and dry graminoids, dicots less than 1.0 cm in diameter and/or those with main stems >1 cm in diameter, but less than 0.50 m in height, and terrestrial members of the Bromeliaceae and Palmae.

All materials within a 0.25 X 0.25 m microplot placed at 5 and 10 m along the 4 central transects were collected, and then overdried at 60 °C for 48 hr (n=32 plots per community). Ten samples from each community were randomly selected for separation into the components listed above. The ratio of each component to the total mass was calculated through separation of 10 randomly selected microplots in each community. The average ratio of each component was used to calculate composition and mass for all samples. Post-fire mass of this layer was collected along each transect at 6 and 11 m, employing the same methods as pre-fire sampling.

Ash mass was calculated through collection of all ash in a 0.50 X 0.50-m plot at 6 m on each central transect (n=16). Ash was collected using a vacuum cleaner and electric generator.

Shrubs

All shrubs with a main stem >1.0 cm in diameter, and > 0.50 m in height but <

2.00 m in height were measured in a 1 X 5-m belt transect established adjacent to the

transects. The height and elliptical crown diameters of all shrubs in each plot were

measured. The elliptic crown area for each shrub was calculated applying the equation:

$$A = \left(\frac{W_1 * W_2 * \pi}{4} \right)$$

where:

A= Elliptic crown area (m^2),

W$_1$= Longest diameter crown (m),and

W$_2$= The longest crown diameter perpendicular to W$_1$ (m).

Crown volume was calculated by multiplying elliptic crown area by height. From

these data, biomass of shrubs was calculated through multiple regression analysis

developed by Kauffman (Appendix 2.2). After fire, the same plots were remeasured

utilizing the same methods.

Trees

All individual trees (> 2.0 m in height) in a 3 x 15-m plot established adjacent to

the transect were measured for diameter and height. Diameter measurements were taken

at height of 0.30 m and 1.30 m. These measurements were made because most studies in

Cerrado refer to a basal area at 0.30 m (Silberbaur and Eiten 1987, Ramos 1990,

Sambuichi 1991, Felfili and Silva Jr. 1993). Thus, the basal area calculated in this study

can be compared with the results of other studies. However, equations used for the

calculation of tree biomass were based on the diameter at 1.30 m. Tree density per

hectare, and mean and range of heights were also calculated. Tree biomass was calculated using the equation presented by Brown et al. (1989) for tropical forests. The regression chosen was for trees of the moist life zone; diameter and height were independent variables. Although this equation was not developed specifically for Cerrado trees, it was judged to be the most applicable. Dr. S. Brown (per. comm.) stated that these equations are very robust; therefore this study provides a preliminary estimate of tree biomass whose accuracy has not yet been determined.

Fire behavior

Weather conditions including ambient temperature ($^\circ$C), relative humidity (%), wind speed (m s^{-1}), direction, and cloud conditions were measured immediately before burning. Fires were ignited as perimeter or circle fires. However, the campo limpo was lighted with a backfire pattern (against the wind), because of high wind speeds at the time of ignition.

Flame characteristics were measured for each fire. At least three random observations of fire behavior were recorded including flame length (distance between the tip of the flame and the ground midway in the zone of active combustion), flame height (vertical distance from the ground to the top of the flame), flame depth (distance at the base of the flame from the leading edge to the rear edge), and flame angle (angle formed between the flame front and the unburnt fuel bed measured off the horizontal) (Appendix 3.2.). In addition, the rate of spread (m min.$^{-1}$), which is the forward rate of movement of the flame front; and residence time (s), which is the length of time for the fire front to pass a point were recorded (Rothermal and Deeming 1980).

With these data, fireline intensity (kW m^{-1}), which is the energy or heat output from flame length of fire front (Bryan 1959), was determined using the formula:

$$I = 258 \, F_L^{2.17}$$

where:

I = Fireline intensity (kW m^{-1}), and

F_L = Flame length (m).

Reaction intensity (kW m^{-2}), which is the rate of heat released per unit area in the active combustion zone, was calculated from:

$$I_R = \frac{I}{D}$$

where:

I_R = Reaction intensity (kW m^{-2}),

I = Fireline intensity (kW m^{-1}), and

D = Flame depth (m).

Moreover, heat per unit area, defined as the direct heat on the surface was calculated (Rothermel and Deeming 1980 and Alexander 1982) from:

$$H_A = \frac{60 \, I}{R}$$

where:

H_A = Heat per unit area (kJ m^{-2}),

I = Fireline intensity (kW m^{-1}), and

R = Rate of spread (m min^{-1}).

Moisture content

Samples to determine moisture content of vegetation and the soil surface were collected before burning. Samples were placed in an air-tight soil container and weighed in the field to determine fresh weight. In the lab, samples were dried at 100 °C for 24 hours and reweighed to determine dry weight. Moisture content was determinate on a dry weight basis, applying the equation:

$$MC = \left(\frac{fw - dw}{dw} \right) * 100$$

where:

MC = Moisture content (%),

fw = Field weight (g), and

dw = Dry weight (g).

Analysis of Variance (ANOVA) was applied to test for differences in total biomass and in the individual components of biomass among plant communities. I found that means were correlated positively with the variance (i.e. greater means were followed by greater variance). Therefore, data were log-transformed prior to analysis (Sokal and Rohlf 1981). However, results of the ANOVA with log-transformed data were not different from original data at 90 % of confidence level, so results are presented here without the transformation. If significant differences in communities were found, the least significant difference, a multiple range test, was applied, and differences among communities determined (p-value = 0.10).

Results

Pre-fire biomass

Pre-fire total aboveground biomass (TAGB) in this study increased significantly

from the grassland (campo limpo and campo sujo) to the woodland communities (cerrado

aberto and cerrado denso) (Table 2.1.). The composition of aboveground biomass varied

among communities. Total graminoids (live and dormant grass combined) were

significantly greater in the campo limpo and campo sujo grasslands than in the cerrado

aberto and cerrado denso. Biomass of graminoids in campo limpo accounted for 72 % of

its TAGB, while in campo sujo, it accounted for 45 %. In contrast, cerrado aberto and

cerrado denso had 8 % and 7 % graminoids, respectively (Table 2.1., Figure 2.1.).

Cerrado aberto and cerrado denso had significantly greater litter biomass than campo

limpo and campo sujo. Litter in campo sujo comprised the greatest proportion of its total

biomass (Figure 2.1.). Biomass of small dicots, palms and bromeliads was significantly

higher for cerrado aberto than for other communities (Table 2.1.). Dead downed wood

debris was not present in the grasslands. Total wood debris comprised 7 % of TAGB of

cerrado aberto and cerrado denso (Table 2.1.).

Cerrado aberto had the highest shrub density, mean height, height range, basal

area per tree, and basal area per hectare followed by cerrado denso and campo sujo

(Table 2.2.A). Consequently, cerrado aberto also had the highest shrub biomass (Table

2.1.). Tree density was also highest in cerrado aberto; however, height (mean and range),

individual basal area, and basal area per hectare were lower than in cerrado denso (Table

2.2.B). Tree biomass was statistically greater for cerrado denso (12,915 kg ha^{-1}) than for

cerrado aberto and campo sujo. (Table 2.1.)

Table 2.1. Total aboveground biomass (kg ha^{-1}) before, after fire, and combustion factor (%) along a vegetation gradient in Cerrado near Brasilia, DF, Brazil (August-October, 1993). Numbers are mean ± standard error.

component	campo limpo			campo sujo			cerrado aberto			cerrado denso		
	pre fire	post fire	C. factor	pre fire	post fire	C. factor	pre fire	post fire	C. factor	pre fire	post fire	C. factor
HERB LAYER												
dicot litter	629 ±57 a	0	100.0 ±0.0	1,907 ±311 b	0	100.0 ±0.0	3,809 ±306 c	7 ±7	99.9 ±0.1	3,275 ±254 c	1 ±1	99.9 ±0.1
dry graminoids	2,021 ±140 a	0	100.0 ±0.0	3,402 ±313 b	0	100.0 ±0.0	1,712 ±194 ac	0	100.0 ±0.0	1,371 ±124 c	0 ±0	100.0 ±0.0
green graminoids	1,934 ±141 a	158 ±36 A	90.1 ±2.2 A	783 ±94 b	50 ±14 B	89.7 ±3.6 A	285 ±28 c	14 ±3 B	94.5 ±1.3 A	290 ±26 c	25 ±7 B	90.7 ±2.4 A
total graminoids	3,955 ±277 a	158 ±36 A	95.6 ±1.0 A	4,185 ±363 a	50 ±14 B	98.7 ±0.4 B	1,997 ±214 b	14 ±3 B	99.2 ±0.2 B	1,670 ±141 b	25 ±7 B	98.3 ±0.4 B
dicot, palm and bromelia	958 ±104 a	284 ±219 A	95.9 ±1.3 A	1,430 ±224 a	135 ±34 A	88.9 ±3.4 A	4,547 ±1,270 b	280 ±110 B	89.9 ±3.6 A	2,043 ±220 a	288 ±93 A	90.1 ±2.9 A
WOOD DEBRIS												
0-0.64 cm	-	-	-	•	•	•	295 ±46	26 ±7	89.0 ±2.9 A	288 ±28	53 ±8	78.6 ±3.5 B
0.65-2.54 cm	-	-	-	•	•	•	621 ±75	194 ±44	62.0 ±8.0	572 ±70	229 ±37	53.1 ±7.5
>2.54 cm	-	-	-	•	•	•	829 ±124	400 ±116	41.7 ±9.8	1,001 ±175	543 ±165	39.2 ±9.7
total	-	-	-	•	•	•	1,746 ±162	620 ±134	66.7 ±6.2	1,860 ±206	825 ±167	55.4 ±5.9
SURFACE LAYER												
herb layer+woody debris	5,542 ±322 a	442 ±270 A	91.6 ±5.3 A	7,523 ±548 ab	185 ±41 B	97.1 ±0.7 A	12,099 ±2,039 b	920 ±196 AB	91.6 ±2.5 B	8,838 ±833 ab	1,138 ±206 B	87.2 ±20.5 A
SHRUB												
leaf biomass	-	-	•	238 ±45 a	9 ±9	98.5 ±1.5 A	772 ±69 b	93 ±40	89.4 ±3.8 B	390 ±45 c	69 ±22	82.5 ±5.8 B
total biomass	-	-	-	1,690 ±346 a	1,112 ±237 A	26.5 ±5.7 A	6,164 ±555 b	3,918 ±415 B	34.6 ±4.6 A	3,190 ±471 c	2,926 ±441 B	9.6 ±1.3 B
FUEL LOAD	5,542 ±322 a	442 ±270 A	91.6 ±5.3 A	7,761 ±734 b	193 ±39 A	96.7 ±2.9	12,870 ±901 c	1,016 ±1,016 B	91.5 ±2.3	9,229 ±85 b	1,207 ±215 B	87.0 ±2.1
TREE	-	-	-	132 ±91 a	132 ±91 A	0.0	6,584 ±1,749 b	6,584 ±1,749 B	0.0	12,915 ±2,451 c	12,915 ±2,451 C	0.0
TOTAL												
surf.layer+shrub+tree	5,542 ±322 a	442 ±270 A	91.6 ±5.3 A	9,344 ±841 b	1,428 ±125 B	84.3 ±1.2 B	24,847 ±2,459 c	11,422 ±1,242 C	53.7 ±3.7 C	24,944 ±2,943 c	16,979 ±2,648 C	33.0 ±3.4 C
ASH		403 ±10 A			1,283 ±94 B			2,273 ±258 C			1,488 ±171 C	

Different lower case letters denote a significant difference (P ≤ 0.10) in biomass, when testing between treatments before fire. Different upper case letters denote difference in biomass after fire (P ≤ 0.10). Different underlined uppercase letters denote a significant difference between combustion factors (P ≤ 0.10) between treatment. The absence of letters mean no differences were found. Dashes ("-") denote that components were not found in the community.
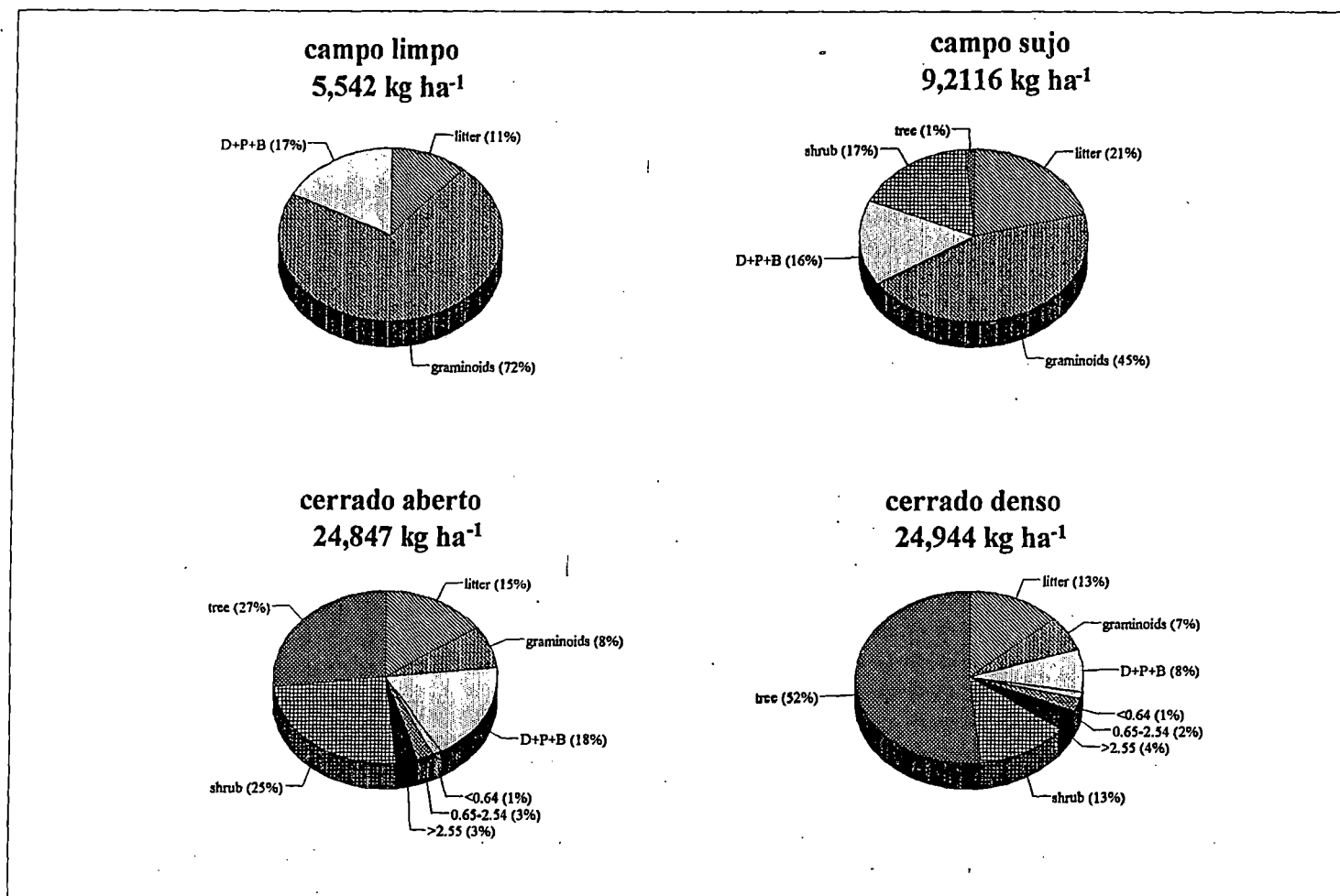
Figure 2.1. Relative proportion of total aboveground biomass components in Cerrado gradient , near Brasilia, DF, Brasil. August-October 1993. D+P+B refers to dicots, bromeliads and palms.

Table 2.2. Shrub (A) and tree (B) density, height and basal area of three community types along a vegetation gradient in Cerrado *sensu lato*. Numbers are mean ± standard

(A)

	campo sujo	cerrado aberto	cerrado denso
SHRUBS			
Density (shrub ha^{-1})	650±80 a	1347±110 b	844±97 c
Height (m)			
mean	0.81±0.34	1.05±0.04	0.93±0.05
range	0.13 - 1.43	0.50 - 1.94	0.55 - 1.77
Basal area/shrub (cm^2)	66.4±14.4	82.6±8.70	74.7±19.1
Basal area/ha (m^{2}ha^{-1})	4.3±0.9 a	11.1±1.6 b	6.0±1.3 c

(B)

	campo sujo	cerrado aberto	cerrado denso
TREES			
Density (trees ha^{-1})	28±28 a	1069±124 b	1000±109 b
Height (m)			
mean	2.5±2.5 a	2.92±0.11 b	3.09±0.35 b
range	2.4-2.5	2.01-6.00	2.01-10.00
Basal area/shrub (cm^2)	0.0096±0.0017 a	80.2±12.5 b	145±16.9 c
Basal area/ha (m^2 ha^{-1})	0.0012±0.00083 a	8.5±2.1 b	14.5±2.5 c

Different letters denote a significant difference (P$\leq$0.10) among communities for both table and (B). The absence of letters mean no differences were found.

Fuel load, defined as the portion of aboveground biomass susceptible to fire (e.g. surface layer plus shrub leaves) (Kauffman et al. 1994), in campo limpo was the same as TAGB. Fuel load significantly increased from campo sujo to cerrado aberto and decreased in cerrado denso (Table 2.1.).

Fire behavior

Weather conditions were similar at the time of burning for all communities, except for campo limpo, which had higher wind speeds (8-10 km h^{-1}). Ambient temperatures ranged from 27 °C to 32 °C, and relative humidity averaged 36 % (Table 2.3.).

Mean moisture content of graminoids, the dominant component responsible for sustained ignition and spread, was very high in campo limpo (52.7 %), while campo sujo had the lowest moisture content (8.9 %). Wood debris and litter were the components with the lowest moisture content in cerrado aberto and cerrado denso (Table 2.3.).

Fire behavior in each community differed. Flame length ranged from 1.4 m to 3.4 m. Flame height and fireline intensity increased from campo limpo (557 kW m^{-1}) to cerrado denso (3,693 kW m^{-1}). Reaction intensity increased from campo limpo to cerrado denso (506 to 1,319 kW m^{-1}) (Table 2.4.).

Consumption

The combustion factor, defined as the percent of biomass consumed by fire, was 91 % and 84 % for campo limpo and campo sujo, respectively. In both campo limpo and campo sujo, litter and dormant grass were completely consumed by fire with small

Table 2.3. Weather conditions and fuel moisture content (%) at the time of prescribed burning along a vegetation gradient of Cerrado *sensu lato*, near Brasilia, DF, Brazil. Data are means ± standard error.

	campo limpo	campo sujo	cerrado aberto	cerrado denso
DATE OF BURNING	7 October 1993	17 August 1993	30 August 1993	31 August 1993
WEATHER CONDITIONS				
Temperature (°C)	27	27	32	30
Relative humidity (%)	40	37	35	31
Wind speed (km/h)	5-6	. N/A	0-5	0-3
Wind direction	S-N	S-W	N	N
General conditions	cloudy	clear	-	hazy, partly cloudy
FUEL MOISTURE CONTENT (% dry weight basis)				
graminoids	52.70±3.11	8.93±1.14	26.85±6.96	24.46±4.73
dicot	114.33±11.75	113.47±8.26	110.89±4.31	136.69±5.20
woody debris	-	-	4.87±1.51	6.04±1.03
litter	-	-	4.75±0.25	5.44±0.97
soil	32.97±0.86	33.06±1.31	19.95±1.95	18.02±0.80

Dash ("-") means that component was not present in that community. N/A means that data was not collected.

Table 2.4. Fire behavior along a vegetation gradient of Cerrado, near Brasilia, DF, Brazil. Data are means $\pm$ standard error.

	campo limpo	campo sujo	cerrado aberto	cerrado denso
Flame length (m)	1.4±0.2	2.8±0.5	3.1+0.4	3.4±0.3
Flame height (m)	1.2±0.2	2.2±0.5	2.7±0.3	2.9±0.4
Flame depth (m)	1.1±0.3	3.0±2.0	3.8±0.4	2.8±0.3
Flame angle (degree)	52.5±7.1	45.0±0	63.2±4.3	61.8±6.4
Rate of spread(m/min)	2.0±1.0	N/A	13.8±2.4	13.8±(0.3
Residense time (s)	2.0±1.0	N/A	31.6±1.8	28.5±6.8
Fire line intenity (kW/m)	556.9	2436.8	3093.8	3692.7
Reaction intensiy (kW/m²)	506.3	812.3	814.2	1318.8
Heat per unit area (kJ/m²)	278.5	-	224.2	267.7

N/A means that measurements were not taken. Statistics were not applied because sample sizes were too small.

amounts of green grass and dicots remaining after fire in both communities. The combustion factor of dormant grassland and litter components in cerrado aberto and cerrado denso was 100 % and 99 %, respectively. Higher consumption rates were measured for smaller diameter classes of wood debris. Consumption of woody debris was > 82 % in all communities. In campo sujo, shrub leaves had the highest combustion factor (98%), and was significantly different from cerrado aberto and cerrado denso. Considering total shrub biomass (stem and leaves) cerrado aberto had the highest consumption (35 %). Fuel loads consumption was high for all communities (>87 %), and differences were not detected among communities (Table 2.1.).

Post-fire biomass

After fire, TAGB of campo limpo and campo sujo differed significantly between themselves and from cerrado aberto which in turn was different from cerrado denso (Table 2.1.). Shrub stems and trees comprised the dominant biomass component in cerrado aberto and cerrado denso after fire.

Fuel load was found in small amounts after fire. In campo sujo, it declined to 193 kg ha^{-1}, while cerrado aberto had 1,016 kg ha^{-1}, and cerrado denso had 1,207 kg ha^{-1}. Ash mass had greatest quantity in cerrado aberto and cerrado denso, while ash mass in campo limpo was the lowest (Table 2.1.).

Discussion

Pre-fire biomass

The Brazilian Cerrado s.l. comprises a variety of vegetation communities, each with a unique composition, and structure (Eiten 1972). This variable community structure, ranging from a grassland (campo limpo) to woodland (cerrado denso), results in differences in biomass of components, fuel load, and TABG within each community type. Kauffman et al. (1994) reported a fuel load of 7,128 kg ha^{-1} for campo limpo, 7,321 kg ha^{-1} for campo sujo; 8,625 kg ha^{-1} for campo cerrado, and 10,031 kg ha^{-1} for cerrado *sensu stricto*. In my study, campo sujo had a similar fuel load, while campo limpo had lower fuel load. Cerrado aberto and cerrado denso fuel load was little higher than fuel loads in campo cerrado and cerrado *sensu stricto* found by Kauffman et al. (1994) Although, the same area was studied, yearly variation in productivity may occur due to different environmental conditions.

In this study, TABG increased as the shrubs and trees increased along the Cerrado gradient. The TABG for cerrado denso (24,944 kg ha^{-1}), which was the highest among the four communities, was quite low compared to other Brazilian forest ecosystems. For example, TABG of Caatinga, a tropical dry forest, is 74 Mg ha^{-1} (Kauffman et al.1993). TABG of Amazonian tropical rain forest is estimated from forest inventory data to be 263 Mg ha^{-1} and 252 Mg ha^{-1} for Para and Rondonia states respectively (Brown and Lugo 1992). Direct measurements, including trees < 0.10 m in diameter at breast height, palms, dead coarse wood debris, in a primary slashed forest is reported to range from 290 to 435 Mg ha^{-1} in the states of Rondonia and Para (Kauffman et al 1995). Comparative estimates of TABG for Cerrado s.l. are scarce. Based upon fuel wood inventories, Fearnside (1992) estimated TABG for Cerrado to range from 11 to 52 Mg ha^{-1}. Although

biomass estimated here for cerrado aberto and cerrado denso is within the range proposed by Fearnside (1992), both must be viewed with caution, given shortcomings in biomass estimation techniques. In my study, tree biomass was calculated from regression equations developed for tropical moist forest. Given differences in structures between Cerrado and moist forest, the degree of error in estimation is unknown (Brown et al. 1989).

Studies that partition and describe TABG into components are rare for Cerrado s.l. (Kauffman et al. 1994). Among vegetation communities in this study, a great variability in biomass ecosystem components existed. For example, cerrado aberto and cerrado denso had a similar TABG; however, the biomass of shrubs and trees differed. The biomass of the graminoids and herbaceous layer decreased with the occurrence of shrubs and trees. This decrease in the live understory vegetation may be less affected by soil moisture or nutrient competition than by light, limiting competition with the overstory (Coutinho 1978b). Although there is a decrease, an herbaceous layer still existed in the denser tree community studied here (cerrado denso). Cerrado trees typically have large and few leaves especially when compared with tropical moist forest trees. This results in less light attenuation by the overstory tree canopy, thereby allowing a herbaceous layer to develop (Eiten 1972). Conversely, litter increased along the gradient from campo limpo to cerrado denso as a consequence of increasing shrub and tree biomass. Wood debris were present in the communities where occurrence of shrubs and trees were abundant.

Fire behavior

Fire had both short- and long term effects on the ecosystem (Muraro 1971 cited in Alexander 1982). The immediate physical effects include the consumption of aboveground biomass and ash deposition. Long term effects may include influences on nutrient pools and cycles within the ecosystem. Nutrient balances are influenced by the incorporation of nutrients from the ash to the soil as well as inputs from precipitation and dry fall (Coutinho 1979, Pivello and Coutinho 1992, Kauffman et al. 1994). The arrangement and quantity of each component found in this study likely influences the flammability and fire behavior of this ecosystem. The fire behavior influence on vegetation composition and structure is related to, and dependent upon the fuel consumption, weather conditions at the time of burning, topography, and fuel moisture content (Chandler et al. 1983, Pyne 1984). Weather conditions were similar for campo sujo, cerrado aberto and cerrado denso. Therefore, differences in fire behavior for these communities are probably due to differences in fuel bed structure, arrangement, quantity and the fuel moisture content. Grass fires potentially have the most rapid rate of spread of all natural fuels (Chandler et al. 1983). This is particularly true when grasses are dry and in a continuous arrangement (Brown and Davis 1973), as was found in campo sujo. Campo sujo was burnt at the end of the dry season; only a slight rain event occurred three days before fire. This likely contributes for the very low moisture content in the graminoids component (8.9 %). Since graminoids comprised 46 % of this community, such low moisture content was responsible for the sustained ignition and spread of fire. Although the rate of spread was not recorded, I suspect that it was very fast because an area of 10 ha burnt in 11 min. With the increase of shrubs and trees in cerrado aberto and cerrado denso, the rate of spread was expected to decline because of changes in fuel composition (decreases in grasses, increases in live fuels and litter). In addition, the

occurrence of a vertical structure likely influenced the microclimate; lower in-stand wind speeds, and higher relative humidity in the understory may influence fire behavior. Conversely, campo limpo was burnt after a series of successive rains in the weeks before the fire. In addition, because of a high wind speeds, it was necessary to use a backfire ignition pattern in campo limpo. This dramatically lowered flame lengths and rate of spread compared to the other communities.

Fireline intensity is used to classify fires and facilitate comparisons of behavior between fires (Alexander 1982). Campo cerrado and cerrado s.s. have been recorded to have 2,842 kW m^{-1} and 3,455 kW m^{-1}, respectively (Kauffman et al. 1994). These are in the range of the energy released in cerrado aberto (3,194 kW m^{-1}) and cerrado denso (3,693 kW m^{-1}) in this study. Fireline intensity is related positively with flaming length, which in turn is responsible for tree scorch height and crown mortality (Van Wagner 1973). Although trees in Cerrado s.l. are well adapted to fire, it was observed that some tree leave, which escaped from fire, lost their leaves due to lethal scorch temperature. Ramos (1990) reported that fire resulted in leaf loss of shrubs that were not consumed by fire. Flame length in campo limpo (1.4 m) and in campo sujo (2.8 m) fell in the range reported for African grassland (Trollope 1978); a backfire technique resulted in 0.5-1.5 m, while flames heading wind had a mean of 2.8 m. Heat per unit area is used to measure the heat the surface, and results may influence future soil environment (Rothermel and Deeming 1980). Although soil far below the surface is not affected by the high temperature, heating of the surface ground may increase nitrogen mineralization, microbial activity, and pH (Kauffman et al. 1992). Consequently, heat per unit area may influence nutrient availability for plant recovering of determined area. Reaction intensity for campo sujo (812 kW m^{-2}) and cerrado aberto (814 kW m^{-2}) were similar. However, it is unlikely that fire effects for these two community types would be similar, because fireline intensity and depth were different. Parameters such as fireline intensity, heat per

area, and reaction intensity must be interpreted together, considering yet rate of spread to have an acceptable description of fire behavior (Alexander 1982).

Consumption and post-fire biomass

In campo limpo and campo sujo almost all of the aboveground biomass was consumed because composition of these communities was predominantly highly flammable grasses. Grasses were in a continuous horizontal layer that facilitated an efficient spread of fire through the ecosystem. The lower combustion factor in the cerrado aberto and denso was related to a less efficient combustion of wood debris, shrub branches, and trees that were either partially burned or unburned in the area after fire. Although consumption of the herbaceous layer and shrub leave was high in my study, complete mortality of vegetation in cerrado is extremely rare when under a natural fire-return interval. (Ramos 1990). Ramos did not find any differences in mortality of individual shrubs and trees when comparing an area of Cerrado protected from fire with an area of biennial burns.

Among Brazilian ecosystems, Cerrado vegetation, especially woodland communities, has the lowest consumption (53 % in cerrado aberto, 33% in cerrado denso). In contrast, Caatinga, a tropical dry forest in Northern of Brazil ranged from 77 to 89 % of aboveground consumption, depending on the season of burning (Kauffman et al. 1993). Slashed primary forest accounted for consumption of between 42 and 57 %. (Kauffman et al. 1994). Consumption of slashed second growth tropical forest is probably higher because its structure is lower. Since plant biomass consumption results in CO_2 release to atmosphere, individual fires in Cerrado vegetation do not cause much of an immediate increasing of CO_2 in the atmosphere compared with other tropical ecosystems.

Ash mass appeared to be related to pre-fire fuel biomass, and hence consumption. The variability of ash composition also depended upon the pre-fire fuel biomass. Fine particles found in campo limpo and campo sujo ash were a consequence of the high consumption of graminoid material. Cerrado aberto and cerrado denso ash was composed of fragments of charcoal, burned twigs and leaves. Smoldering combustion observed in cerrado aberto was principally in wood debris > 2.54 cm in diameter. It is expected that a portion of the ash (mineralized nutrients) is incorporate into the soil while some is lost via the wind and water to adjacent areas.

Conclusion

Total aboveground biomass and composition in the Cerrado s.l. near Brasilia, Brazil, varied along a vegetation gradient of increasing wood structure. The grasslands, campo limpo and campo sujo had little, if any, shrubs and trees; consequently, their total aboveground biomass was lower than that of cerrado aberto and cerrado denso. This composition and arrangement combined with moisture content and weather conditions appeared to influence fire behavior in Cerrado s.l..

Fire plays a dominant ecological function in this ecosystem, and it is important in shaping the different communities. Descriptions of fire behavior were different for each community type. In this study, fireline intensity was lower for grassland than for wood communities.

Total biomass of Cerrado s.l. in this study was found to be the lowest mass among tropical forests in Brazil. As vegetation is a source and sink of C, combustion results in the release of these stored C and mineral nutrients. Consequently, the contribution of the Cerrado s.l. to the increase of CO_2 and to the greenhouse effect is probably the lower on

the basis of area than that of other Brazilian ecosystems. Moreover, Cerrado vegetation recovers rapidly after fire resulting in C uptake to pre-fire levels in one to two years. These combined with the well-adapted morphological and reproductive traits of Cerrado vegetation may indicate fire as a natural disturbance in this ecosystem.

To understand the fire ecology of Cerrado vegetation, it is essential to learn its function, dynamics, nature and variability. Fire may enhance habitats by creating seed beds, controlling diseases and pests, and reducing a wild fire hazard. However, this will vary by vegetation community type resulting in even a higher level of diversity.

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CHAPTER 3
ROOT BIOMASS IN CERRADO VEGETATION NEAR BRASILIA, BRAZIL

Abstract

Deforestation and conversion to agriculture is occurring in vast areas in the Cerrado *sensu lato* (a tropical savanna ranging from pure grasslands to woodlands), yet few studies have quantified total biomass or nutrient pools in this ecosystem. Root biomass was quantified along this gradient in four plant communities at the Instituto Brasileiro de Geografia e Estatística (IBGE) Ecological Reserve, and the Jardim Botânico de Brasilia (JBB) Ecological Reserve, both in Brasilia, DF, Brazil.

Root biomass increased from the pure grassland, campo limpo (16,317 kg ha^{-1}) to woodland, cerrado denso (52,907 kg ha^{-1}). The proportion of the total root biomass in the upper 20 cm of soil was 63 % for campo limpo, 73 % for campo sujo, 79 % for cerrado aberto and 62 % for cerrado denso. More than 80 % of root biomass occurred in the upper 30 cm of the soil, except for cerrado denso (71 %).

Fine roots (≤ 0.5 cm in diameter) dominated in grasslands and decreased in the woodlands. In campo limpo, fine roots were 56 % of its total root biomass, campo sujo was 46 %, cerrado aberto was 40 % and cerrado denso was 29 %. Nevertheless, coarse root class diameter (≥ 0.6 cm in diameter) increased from campo limpo to cerrado denso.

Root:shoot ratio in communities was very high indicating that more than 71 % of its live phytomass (aboveground biomass + root biomass) is in the belowground. These results were unique for tropical ecosystems. Root:shoot ratios in the Cerrado *sensu lato* were among the highest for tropical ecosystems. This is likely related to survival strategies associated with frequent fires and severe dry seasons typical of this ecosystem. These belowground pools may be significant sources of carbon (C) pools when Cerrado *sensu lato* is converted to agriculture.

Introduction

In most ecosystems of the world roots have not received the same level of study as aerial parts of plants (Russel 1977, Sanford 1989). This lack of attention is related to the time consuming methods associated with excavations, and to the necessity of disturbance in the study area (Santantonio et al. 1977). Functions of roots and belowground tissues include uptake and storage of water and nutrients (Jesko 1992). Roots are significant sink of the carbon (C) fixed by aboveground tissues. For example, in a temperate deciduous (*Liriodendron*) forest, 45 % of all C fixed is used in the production of root biomass and root respiration (Harris et al. 1972). Since roots are part of the ecosystem, a better knowledge of their biomass and distribution is important to understand C dynamics of the whole ecosystem. Issues of the relationship between increasing atmospheric CO_2 and climate change, and accelerated levels of tropical deforestation require better quantification of the total aboveground and belowground biomass pools (Fearnside 1992).

Root biomass has been quantified in few neotropical ecosystems. In the tropical dry forest, total root biomass has been estimated to range from 31 to 45 Mg ha^{-1} (Murphy and Lugo 1986, Castellanos et al. 1991). In the Venezuelan Amazon tropical rain forests, Sanford (1989) reported root biomass ranges from 54.6 to 60.9 Mg ha^{-1} in three different forest community types. In Brazil, Para state, Nepstad (1989), compared root distribution in an intact tropical rain forest and a grass/shrub vegetation, finding 35.4 and 9.7 Mg ha^{-1} respectively.

A gradient of grassland to woodland known as Cerrado *sensu lato* comprises 23 % of Brazil area. Like tropical savannas, it evolved with a history frequent fire under a nutrient poor soils and in a climate with marked wet and dry seasons.

In Cerrado s.l., root systems of individual species were classified as deep-rooted, shallow-rooted and medium-rooted (Rawitscher 1948). Rachid-Edwards (1956) described underground adaptations to drought and fire for selected species of the Poaceae family. Descriptions of subterranean organs and their potential of vegetation reproduction were discussed by Rizzini and Heringer (1961, 1962). However, total root biomass in this ecosystem has not been investigated. I hypothesized that among adaptations to frequent fire, annual drought, and poor soil nutrients, a greater portion of resources would be sent to the belowground system, so that root biomass and root:shoot ratios would be high relative to other tropical ecosystems.

The objectives of this study were to (a) quantify and compare the total root biomass along four communities types varying from grasslands to woodlands, (b) quantify the vertical root distribution down to soil depth of 2.00 m for each community type, (c) quantify the diameter size distribution of roots, and (d) compare root biomass with total aboveground biomass data and describe root:shoot ratio for communities along this Cerrado gradient.

Study Site

Research was conducted at the Reserva Ecológica do Instituto Brasileiro de Geografia e Estatística (IBGE Ecological Reserve) and the Jardim Botânico de Brasilia (JBB Ecological Reserve). These sites are located about 35 km south of Brasilia, in Brazil (15° 51' S 47° 63' W). The elevation is 1,100 m and slopes are < 10%. From 1980 to 1992, mean annual temperature varied from 19.2 °C to 22.4 °C. Mean precipitation was 1482 mm distributed in two distinctive seasons: a wet season from October to March with 1257 mm and the dry season from April to September with

225 mm. Mean maximum relative humidity was 81% in December and the mean minimum was 55% in August (File data from Estação Agroclimatológica do IBGE 1980-1992).

Soil in these areas are poor in nutrient concentration, with high aluminum content, and high pH. Vegetation is characterized by the five community types described for Cerrado s.l., i.e. campo limpo (grassland), campo sujo (grassland with scarce shrubs), campo cerrado (dominance of shrubs with scattered trees and some grasses), cerrado *sensu stricto* (s.s) (dominance of trees with scattered shrubs and some grasses), and cerradão (a closed canopy forest) (Eiten 1972, Coutinho 1978b, Goodland and Pollard (1973). Moreover, within cerrado s.s., areas with a more open tree canopy are referred here as cerrado aberto and those with a more closed canopy as cerrado denso variations with a more open(cerrado aberto) and closed tree canopy (cerrado denso) than cerrado *s.s.* is also found. In this study, root biomass was investigated in campo limpo, campo sujo and in the two variants of cerrado s.s.: cerrado aberto and cerrado denso.

Methods

Root biomass was quantified by a combination of monolith and auger methods (Böhn 1979). A trench was dug prior to root excavation and at the top of one side wall, an area of 0.50 x 0.50 m was marked and all aboveground vegetation was clipped and removed. From this side wall, into this area, roots within this monolith were excavated by layers (0-10 cm, 10-20 cm, 20-30 cm, 30-50 cm and 50-100 cm). From 100 cm to 200 cm an auger of 15 cm in diameter was used. Five samples (five holes) per community type were systematically selected and measured.

All material (soil and roots) was sieved in the field. Roots were taken to the laboratory, and dried at 60 °C for 48 hours. Later, roots were separated into five classes

according to diameter: ≤0.5 cm, 0.6-1.0 cm, 1.1-2.0 cm, 2.1-3.0 cm, and tubers. Tubers included all other root structures found in Cerrado s.l., such as tubercle roots, xylopodia, lignotubers and rhizome. Finally, the material was weighed.

The study was established in a systematic design. In a linear arrangement five holes were dug approximately 20 m apart. While most samples had a normal distribution, homogeneity of variances did not occur (Barlett's test, p-value ≥ 0.10). Therefore, a non-parametric Kruskal-Wallis test was applied to test for differences among root biomass of community types (p-value = 0.10). If significant, a Mann-Whitney test was applied to separate the treatments (Sokal and Rohlf 1981). Medians and means were similar, indicating that samples differed in variance yet were normally distributed, therefore, means are used in the text, tables and graphics.

Results

Total root biomass in the Cerrado gradient, near Brasilia, Brazil, increased from the campo limpo (grassland) to cerrado denso(woodland). Total root biomass for campo limpo and campo sujo were significantly different from cerrado aberto and cerrado denso (Table 3.1.).

Distribution of root biomass by depth for each community was similar with root biomass tending to decrease with soil depth. This decrease was most dramatic in campo limpo, the community without woody vegetation (Figure 3.1.).

Along the vegetation gradient from grassland to woodland, the relative concentration of roots in the top 10 cm was approximately 50 % for campo limpo, campo sujo, and cerrado aberto, and 31 % for cerrado denso. In contrast at a depth of 10-20 cm, the proportion of root biomass increased from campo limpo (10 %) to cerrado denso (31 %).

Table 3.1. Total root biomass (kg ha⁻¹) along the Cerrado *sensu lato* in Brasilia, DF, Brazil.

communities	Root biomass		
	mean ± SE		median ± QD
campo limpo	16,317 ±2,519	a	16,274 ±1,534
campo sujo	30,083 ±4,594	a	30,270 ±6,516
cerrado abërto	46,584 ±6,135	b	41,938 ±3,775
cerrado denso	52,908 ±8,429	‑b	49,713 ±15,986

Different letters denote significant differences (p-value < 0.10) in biomass when testing between communities using Mann-Whitney test.   Means are followed by standard error, and medians are followed by quartile deviation (N=5).   The rough similarity between means and medians indicate that root biomass distribution was not too skewed.
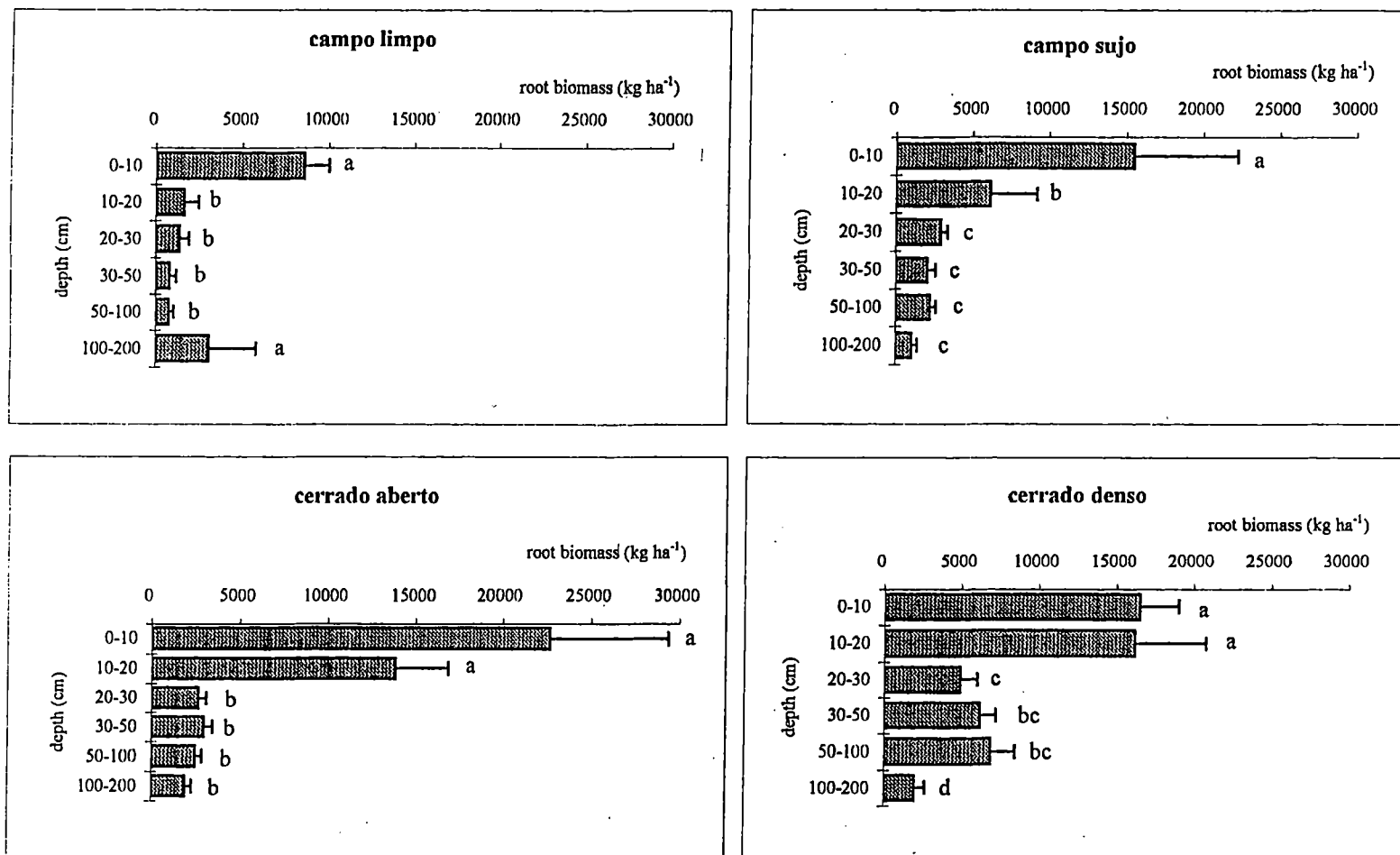
Figure 3.1. Root biomass distribution by depth in Cerrado *sensu lato*, near Brasilia, Brazil. Different letters refer to significant differences in biomass by depth within each community (p-value = 0.10).

Most of the roots were concentrated in the first 20 cm in depth for all communities;
campo limpo had 63%, campo sujo 73 %, cerrado aberto 79 %, and cerrado denso 62 %.
In cerrado denso, 71 % of the total root biomass was found in the upper 30 cm of soil. In
all other communities it was more than 80 %. Roots in the 30-50 cm soil depth
comprised 5 to 12 % of the total root biomass. At depths of 50-100 cm, roots comprised
5 to 13 % of the total pool. Only 3 to 4 % of the total pool was at a depth of 100-200 cm
except in campo limpo, which had 19 % of its total root at this depth.1

Roots $\leq$ 0.5 cm in diameter were the dominant diameter class in term of biomass
along this Cerrado gradient. While biomass of fine roots increased along the cerrado
vegetation gradient, the relative contribution decreased. In campo limpo, campo sujo,
cerrado aberto and cerrado denso roots $\leq$ 0.5 cm comprised 56 %, 46 %, 40% and 29 %
their respective total root biomass. In contrast, the relative abundance of coarse roots
(diameter classes $\geq$ 0.6 cm), increased from campo limpo to cerrado denso. Coarse root
biomass was 7,146 kg/ha (44 %) in campo limpo, 16,275 kg ha^{-1} (54 %) in campo sujo,
27,954 kg ha^{-1} (60 %) in cerrado aberto; 37,518 kg ha^{-1} (71 %) in cerrado denso
(Figure 3.2.). Tubers were present in all communities (Figure 3.2.) comprising 9 % in
campo sujo to 23% in cerrado aberto.

The difference in total root biomass between community types in Cerrado s.l. was
also found for total aboveground biomass for this same study area (Chapter 2). Total
ecosystem phytomass (live aboveground biomass and root biomass) in Cerrado gradient
varied from 19,209 kg ha^{-1} for campo limpo to 71,345 kg ha^{-1} for cerrado denso (Table
3.2.). Campo sujo had the highest root:shoot ratio with 7.7; and cerrado aberto had the
lowest ratio, 2.6 (Table 3.2.).
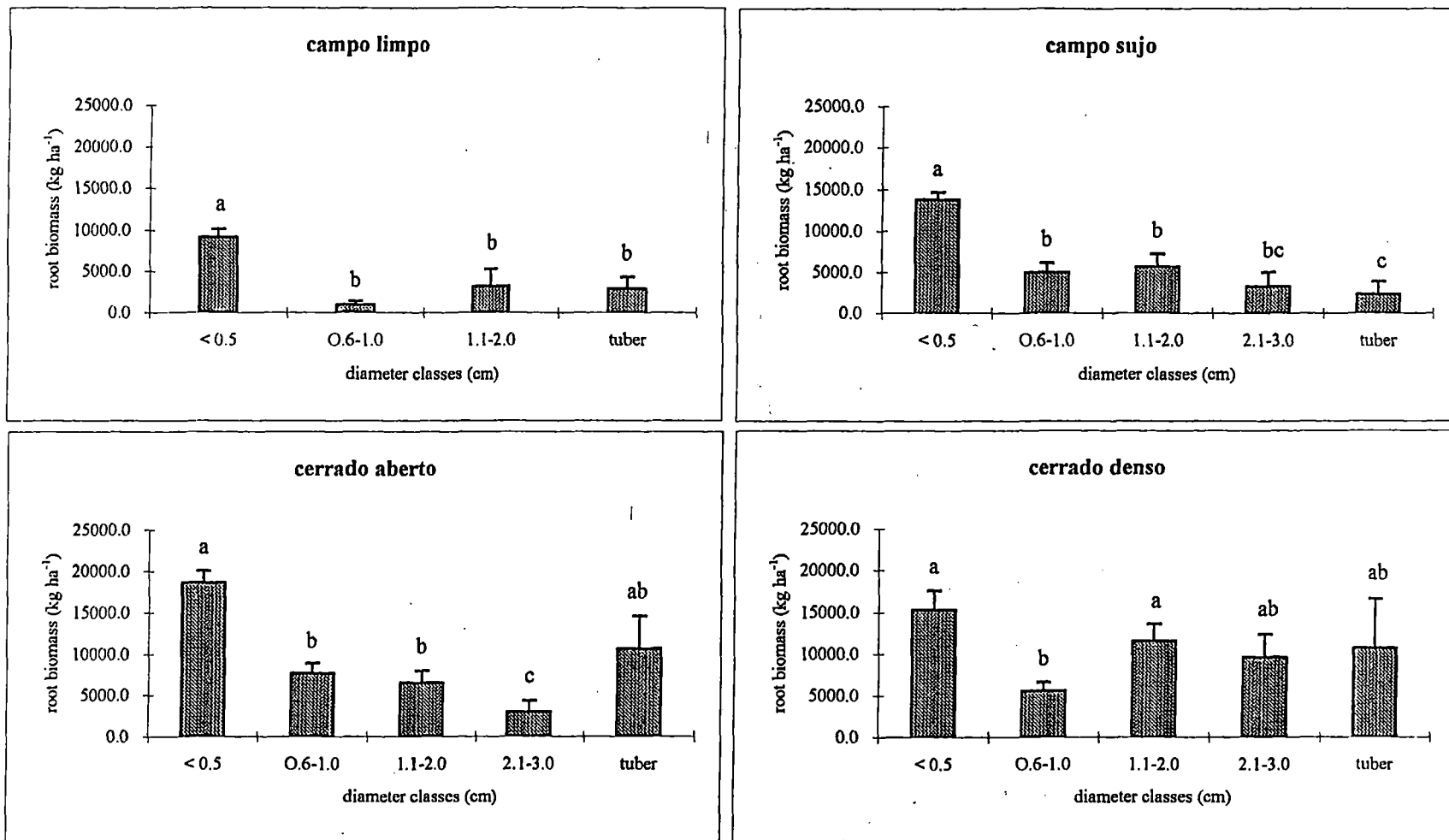
Figure 3.2. Root biomass by diameter in Cerrado gradient, near Brasilia, Brazil. In campo limpo, roots with diameter between 2.1-3.0 cm were absent. Different letters refer to a significant differences in biomass by diameter and tuber within each

Table 3.2. Total phytomass (kg ha^{-1}) of the Cerrado *sensu lato*, near Brasilia,DF, Brazil.

live biomass	campo limpo	campo sujo	cerrado aberto	cerrado denso
green grass	1,934	783	285	290
dicot+palm+bromelia	958	1,430	4,547	2,043
shrub	-	1,690	6,164	3,190
tree	-	132	6,584	12,915
aboveground (shoot)	2,892	4,035	17,580	18,438
belowground (root)	16,317	30,083	46,584	54,908
total phytomass	19,209	34,118	64,164	73,345
root:shoot	5.6	7.7	2.6	2.9

Discussion

The structure and biomass of root systems are related to the species' genetic inheritance and to environmental factors of the ecosystem (Kerfoot 1963, and Richards 1986). Environmental factors affecting root structure and biomass include soil related to soil moisture, macronutrient availability as well as soil physical characteristics (Rizzini and Heringer 1961, Richards 1986). Goodland and Pollard (1973) studied variability in soil chemistry along the Cerrado s.l. as a factor influencing vegetation structure from campo sujo to cerradão (Goodland & Pollard 1973). They found higher nutrient concentration in the soil for community types with greater tree density and basal area. Askew et al. (1971) investigated the soil moisture content along a transect from grassland to woodland in Cerrado s.l. area of Mato Grosso state, Brazil. Soil moisture content up to 1.05 m in depth was higher for grassland than for woodland during the entire year. Soil classification and a brief association of community vegetation types were described by Haridasan (1990). Most of the cerrado s.s., campo cerrado and campo sujo are related to Latosols (Oxisols) and Podzolic (Afsols or Ultsols) soils; campo limpo is associated with lithosols (Lithic dystropepts) in the upper parts of the valley and with hydromorphic soils (Inceptsols) in the lower parts of the valley. In this study, differences in total root biomass and their variable structure and distribution among communities are likely the response to differences in chemical, physical, and moisture conditions of the soil that these four communities may have, in addition to genetic differences among plant species. The different community structure in the Cerrado gradient tends to reflect the differences in total root biomass. As aboveground biomass increased, root biomass also increased, and structural characteristics of the roots changed. The high amounts of total root biomass found in each community type may be an adaptation to frequent fires and annual drought, as I hypothesized. However, to confirm that hypothesis, comparisonsbetween

Similar community types, with the same environment conditions must be made by treating one with frequent burning while the other remains unburned.

Root biomass in Cerrado s.1. was not described before this study. When compared with other tropical savannas, the range of 16,317 kg ha^{-1} to 52,908 kg ha^{-1} for the Cerrado s.1 found in this study was quite high. Along a vegetation gradient from grassland to woodland in the Venezuelan llanos (a hyperseasonal savanna type which has a period of water shortage during the dry season and a period of excess of water during rain season), root biomass ranged from 11,480 ti 18,910 kg ha^{-1} (Sarmiento and Vera 1979). In Lamto savanna, Ivory Coast, Africa, total root biomass ranged from 10,100 kg ha^{-1} to 19,000 kg ha^{-1} in the same gradient (Menaut and Cesar 1979).

Although total root biomass in the Cerrado s.1 was higher, root distribution by depth was similar to these other tropical savannas. Their root biomass also was conceptrated in the surface soil layer for grasslands and more evenly dispersed though the soil for woodlands (Sarmiento and Vera 1979, Menaut and Cesar 1979). In campo limpo a decrease in root biomass in the deeper layers reflects the distinct root system that graminoids, the principal components in this community, display. Graminoid root systems are typified by shallow and widely spread roots along the top of the layer of soil. In campo sujo, cerrado aberto, and cerrado denso root biomass declined in a more gradual manner with increasing soil depth (Figure 3.1.). This is likely related to the increasing dominance of herbs, shrubs and trees (Table 3.2.) (Chapter 2). In cerrado denso, the greater abundance of roots in the 30 to 100 cm depth suggests a greater exploration of deeper soils. Lawson et al. (1968) reported a similar stratification of roots in Guinea savanna with large diameter roots of shrub and trees at depths of 10-20 cm which were overlain with a zone of grass roots in surface layers. Some species in Cerrado s.1. have been described as shallow-rooted such as *Echinolaena inflexa* (Poir) Chase, *Tristachya leiostachia* Nees (Poacease), and some perennial herbs *Ipomoea villosa* Meissn, (Convolvulaceae), and *Vernonia grandiflora* Less (Compositae). Species with

medium-rooted systems are represented by *Butia leiospatha* (Barb. Rodri.) Becc
(Palmae), and *Jacaranda decurrens* Cham. (Bignoniaceae). Others, particularly
evergreen trees such as *Dimorphandra mollis* Benth (Leguminosae), *Palicourea rigida*
H.B.K. (Rubiaceae), *Qualea grandiflora* Mart. (Vochisiaceae) and *Kielmeyera coriacea*
Mart. (Gutifereae) have been described as deep-rooted (Rawitscher 1948). The great
diversity of species in Cerrado may be the a result of the interspecific coexistence of
species, which allows for maximum explotation of water and nutrients at different depths
because of variable root architecture.

The greatest proportion of the root biomass was concentrated in the top 30 cm of
the soil horizon (more than 80%, except for cerrado denso). This was similar to Lamto
Savanna in Africa where 80 % of the root biomass also occurs in surface soils (Menaut
and Cesar 1979). However, roots have been reported to penetrate as deep as 19 m in the
Brazilian Cerrado (Rawitscher 1948). A concentration of roots in the soil surface may
also be related to the decomposition of organic matter, and the exploitation of nutrients
in an ecosystem that is nutrient poor. Tropical savanna vegetation has a low rate of
decomposition and nutrient availability during the dry season, but a much higher rate
during the wet season (Swift et al. 1979). For cerrado s.s. and cerradão areas, litter
decomposition is also higher during the wet season (Peres et al. 1983). Surface roots can
rapidly capture nutrients available from decomposing organic matter, resulting in a very
closed nutrient cycle in a nutrient-limited ecosystem (Jordan 1985). Leaching of
nutrients during the wet season is thereby minimized. Surface roots also are well adapted
to exploit the increased nutrient availability following frequent low intensity surface
fires. Fire accelerates the process of mineralization of nutrients and increases the
availability of nutrients through this mineralization and though ash deposition (McNabb
and Cromack Jr 1990). Subsequently, a well developed root system in the upper limits of
the soil surface facilitates survival after fire while allowing for rapid exploitation of
available nutrients and limiting losses via leaching.

An important component of Cerrado s.l., fine roots (≤ 0.5 cm) are often related to the abundance of monocotyledons in grassland communities, and associated with herbs, shrubs and trees in the woodland (personal observation). Monocotyledons typically have a fibrous root system with a large number of adventitious roots which have very small diameters (Richards 1986). Monocotyledons form a continuous yet declining layer of biomass along the vegetation gradient from campo limpo to cerrado denso. The aerial biomass of graminoids along this gradient was 3,955 kg ha^{-1} (72 % of aboveground biomass) in campo limpo, 4,185 kg ha^{-1} (46 %) in campo sujo, 1,997 kg ha^{-1} (11 %) in cerrado aberto, and 1,670 kg ha^{-1} (13 %) in cerrado denso (Table 3.2.) (Chapter 2). Fine roots followed a similar decline in their relative contribution to the total root biomass as grasses did to aboveground biomass: 9,171 kg ha^{-1} (56 %) in campo limpo, 13,808 (46 %) in campo sujo, 18,630 kg ha^{-1} (40 %) for cerrado aberto, and 15,336 kg ha^{-1} (29%) for cerrado denso. In cerrado aberto and cerrado denso the increasing predominance of trees and shrubs with tap root systems, and of tubers promoted a greater diversity in the root diameter classes of these communities.

Tubers and other belowground structure occurred in all communities. They are adaptations to insure survival during the dry season through water and nutrient storage (Rizzini and Heringer 1961). Moreover, these belowground organs often possess dormant meristematic tissues (xilopodium) promoting vegetative reproduction. These are important adaptations in this environment with frequent fire. When aboveground tissues are destroyed by fire, shoots arise from xilopodia even in the absence of rain (Rizzini and Heringer 1961). Other species in the Cerrado s.l. have roots that run parallel to the ground (sucker roots) that produce shoots at variable intervals (Rizzini and Heringer 1962). In this study, some roots of 2.0-3.0 cm in diameter fit these description in cerrado aberto and cerrado denso.

Vegetative regeneration from belowground tissues is far more common that sexual reproduction in most grasses, trees and shrubs (Rizzini 1976). Seeds of different

species subjected to a high temperature showed no increase in germination (Rizzini 1976). Seeds from species of herbaceous layer may be released from fruits after fire (Coutinho 1977). However, any established seedlings are subjected to drought, frequent fires and competition (Rizzini and Heringer 1962). Graminoids also have protected belowground buds that insure survival in spite of frequent fires (Rachid-Edwards 1956).

Cerrado s.l. had a high root:shoot ratio compared to tropical ecosystems (Table 3.3.). The high R:S ratio is thought to be an adaptation for drought and poor soil nutrient conditions (Monk 1966). Tropical dry forest, for example exhibit these conditions (Castellanos et al. 1991, Brown and Lugo 1992), however, the R:S ratio in Cerrado s.l. was three times higher.

In the Cerrado s.l., evergreen plants persist in an environment with a pronounced three to five month dry season; therefore, greater quantities of energy are allocated to roots to maximize exploitation of soil volume and hence the ability for water and nutrient absorption (Jesko 1992). Moreover, I think that frequent fire, which stimulates vegetative reproduction in Cerrado s.l., may be important agent in promoting a well-developed root biomass. A higher root:shoot ($\bar{R}$:S) ratio was found in campo limpo and campo sujo (5.6 and 7.7 respectively), in contrast to that of cerrado aberto and cerrado denso (2.6 and 2.9). Root:shoot ratio of large individual species are expected to be lower than that of small species (Bray1963 in Monk 1966). The decrease in the R:S ratio in Cerrado s.l. occurred as woody vegetation increased.

Table 3.3. Root and aboveground biomass (Mg ha $^{-1}$) of different tropical
ecosystem compared with Cerrado *sensu lato* .

ecosystem	tree density	shoot	root	r:s	source
Tropical Savanna					
Cerrado (Brazil)					
campo limpo	-	2.9	16.3	5.6	this study (1)
campo sujo	12	3.9	30.1	7.7	this study
cerrado aberto	1064	17.6	46.6	2.6	this study
cerrado denso	1000	18.4	53.0	2.9	this study
Llano (Venezuela)					
grassland	-	6.0	11.5	1.9	Sarmiento and Vera 1979 (2)
woody savanna	100	5.3	19.0	3.6	Sarmiento and Vera 1979
Ivory Coast (Africa)					
grassland	-	4.6	10.5	2.3	Menaut and Cesar 1979 (3)
woody savanna	250	5.4	13.8	2.6	Menaut and Cesar 1979
Tropical rain forest					
Brazil	10406	264.0	35.4	0.13	Nepstad 1989 (4)
Venezuela	nd	335.0	56.0	0.17	Jordan and Uhl 1978 and Stark and Spratt 1977 (5)
Ghana	5300	233.0	54.0	0.23	Greeland and Kowal 1960 (6)
Tropical dry forest					
Puerto Rico	12000	53.2	45.0	0.84	Murphy and Lugo 1986 (7)
Mexico	4700	73.6	31.0	0.42	Castellano et al. 1991 (8)

(1)- Aboveground biomass includes green grass, herbs, dicots, palms, bromeliads, shrubs and trees.
Roots were measured up to 2.00 m in depth.
(2)- Root biomass was investigated up to 2.00 m in depth.
(3)- Aboveground and root biomass refer to the herb layer in these communities. Roots were
investigated up to 2.00 m in depth.
(4)- Aboveground biomass includes live trees $\geq$ 1.0 cm in diameter, and root biomass was measured
up to 10.0 m in depth.
(5) and (6)- Root biomass was measured up to 0.50 m and 0.90 m in depth, respectively..
(7)- Aboveground biomass includes all live vegetation > 1.50 m in height, standing dead material
and epiphytes.
(8)- Aboveground biomass included trees, shrubs and lianas. Roots were measured to 0.80 m in
depth.

Conclusion

This study investigated for the first time the belowground phytomass for plant communities along a vegetation gradient in the Brazilian cerrado. The increase in root biomass from campo limpo to cerrado denso was similar to earlier findings concerning aboveground biomass in the same study area. Although roots were measured to a depth of 2.00 m, they were concentrated in the upper limits of the soil with ≥ 71 % in the top 30 cm.

Remarkable quantities of phytomass of the Cerrado s.l. were belowground. Reasons for this may be the presence of nutrient-poor soils and periods of drought, high vegetative reproduction stimulated by fire, and better exploitation of nutrients and water by volume of soil. Roots are a reservoir of nutrients, C and water. The allocation and storage of C was different from that of tropical rain forests which have similarly nutrient-poor soils. Consequently, the Brazilian Cerrado gradient may be a more significant global C pool than previously thought. While fires may not result in significant C losses of the Cerrado vegetation, if it is deforested, burned and replaced by crop monoculture, belowground C pools may be depleted. Moreover altering the carbon budget through belowground C depletion, large-scale crop conversions will probably result in great losses of plant diversity in this ecosystem.

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CHAPTER 4
CARBON, NITROGEN, AND SULFUR POOLS, AND DYNAMICS ALONG A
VEGETATION GRADIENT IN THE BRAZILIAN CERRADO

Abstract

Nutrient pools and fire effects on nutrients were investigated in four plant communities of Cerrado *sensu lato* gradient in central Brazil. This gradient consists of campo limpo (pure grassland), campo sujo (grassland with sparse shrubs), cerrado aberto and cerrado denso (both are variants of cerrado *sensu stricto*, which comprises grasses, herbs, shrubs and trees).

Aboveground pools of carbon (C), nitrogen (N) and sulfur (S) varied from 1,933, 15, and 1.7 kg ha^{-1}, respectively, in campo limpo to 12,809, 185, and 15.3 kg ha^{-1}, respectively, in cerrado denso. Root pools were measured to a depth of 2.00 m. Roots $\leq$ 0.5 cm in diameter had the largest pool for all nutrients. Tubers, a subterranean organ of reserve, tended to have the highest concentration of nutrients. Total root nutrient pools were generally at least two times larger than aboveground pools. Cerrado *sensu lato* root C pools ranged from 7,633 to 25,482 kg ha^{-1}; N pools varied from 127 to 369 kg ha^{-1}; and S pools were 8 to 21 kg ha^{-1} for campo limpo and cerrado denso, respectively. Soil nutrient pools accounted for more than 86 % of the total ecosystem nutrients. Campo limpo had the highest C and N soil pools, but S was highest in the cerrado aberto soil pool.

Fire reduced all aboveground pools. Except for N in cerrado aberto, nutrient losses were greater by volatilization than by ash particulate. Losses of nutrients in all ecosystem pools as the result of fire were < 2.0 %.

Compared with other tropical ecosystems, the belowground storage of nutrients in Cerrado was unique that can be a large sink or source of C and other nutrients. Fire in

Cerrado *sensu lato* released 1/10 or less of the nutrients lost from tropical moist and dry forests through slash-and-burning agriculture methods. However, deforestation of Cerrado *sensu lato* may make available to the atmosphere masses of C and nutrients that are currently sequestered in root and soil pools.

Introduction

The Brazilian Cerrado (Cerrado *sensu lato*) is a gradient of plant communities of diverse compositions and structures. This vegetation gradient is comprised of campo limpo (grassland), campo sujo (grassland with sparse shrubs), campo cerrado (open shrub), cerrado *sensu stricto* (a dense scrub made up of shrubs and trees), and cerradão (a forest with a more or less closed tree canopy) (Goodland 1971, Eiten 1972, Coutinho,1978b).

Cerrado s.l. is located in central Brazil and has an areal extent of approximately 2.0 million km^2. Its tropical climate is characterized by distinct wet and dry seasons. Precipitation ranges from 700 to 2000 mm, concentrated between October and March. Temperature varies little during the year, ranging from 20 °C to 26 °C (Eiten 1972). The majority of soils are deep and well drained Latosols, recognized as Oxisols in the American Soil Taxonomy. These soils are nutrient poor, with a high concentration of aluminum and low cation exchange capacity (Alvim and Araujo 1952, Lopes and Cox 1977). In addition to climatic and soil factors, fire has been also considered to be a strong influence on plant structure, composition, and productivity in Cerrado s.l. (Coutinho 1990). Fires have been suggested as a significant influence in the evolutionary history of Cerrado (Lofgren 1898; Warming 1973). Charcoal evidence suggests the presence of fire in the region for at least 8600 years (Coutinho 1981). Burning occurs accidently, intentionally by human ignition, or rarely by lighting. Fire

accelerates nutrient cycling through conversion of organic materials into mineral forms available to plants (Coutinho 1990). Fires also result in nutrient losses to the atmosphere via particulate and volatilization (Kauffman et al. 1994). Carbon (C), nitrogen (N), and sulfur (S) are essential elements present in plant tissues and organic debris, which are easily affected by fire because of their low temperatures of volatilization (Raison et al. 1985, Kauffman et al. 1992). Emissions of C, N, and S from biomass burning of world tropical savannas have been reported to have a strong influence on global atmospheric chemistry (Crutzen and Andreae 1990).

Adaptation to a short fire return interval (two to three years) in Cerrado s.l. includes the ability of plants to persist and/or rapidly recover following fire (Eiten 1972, Pivello and Coutinho 1992). Fire effects on vegetation have been described at community, population, and species levels (Coutinho 1977, Cesar 1980, Raw and Hay 1985, Ramos 1990, Rosa 1990). Nutrient content in the biomass was reported for campo sujo by Batmanian (1983), and for campo limpo, campo sujo, campo cerrado, and cerrado *sensu stricto* by Kauffman et al. (1994). Cavalcanti (1978) recorded soil nutrient concentration of campo cerrado after burning. Concentration of Ca, K, P, and Mg in the top 5 cm in the soil increases after fire and decreases in the following months. Mineral nutrient inputs occur during the rainy season, but fires near a study area may introduce nutrients by dry fall (Coutinho 1979). Season of burning in campo cerrado did not affect in the amount of nutrient losses to atmosphere due to fire (Pivello and Coutinho 1992). Fuel load, fire behavior, and fire effects on nutrient dynamics were described by Kauffman et al. (1994). However, total aboveground nutrient pool, root nutrient pool and total ecosystem nutrient pools of Cerrado s.l. have not been described.

Natural vegetation of Cerrado s.l. has been changing at accelerating rates. Thirty-seven percent of Cerrado s.l. is already modified by cities, dams, mining, abandoned agriculture, and also by the cultivation of pastures, soybeans, corn , rice,

coffee and eucalyptus (Dias 1990). Given this level of land-use conversion and the extent of burning, data on nutrient pools are important in order to understand the significance of the Cerrado ecosystem both as source and sink for carbon and other nutrients.

In order to understand the consequences of fire and land use on the nutrient dynamics, the following objectives were established: (1) to quantify C, N, and S nutrient pools in the aboveground biomass for four plant communities of the vegetation gradient of cerrado *sensu lato*; (2) to quantify belowground (soil and roots) C, N, and S pools for each community type; and (3) to quantify losses of nutrients to the atmosphere during fires, and amounts remaining following fire for each community type.

Study Site

The research was conducted at the Reserva Ecológica do Instituto Brasileiro de Geografia e Estatística (IBGE Ecological Reserve) and at the Estação Ecológica do Jardim Botânico de Brasilia (JBB Ecological Reserve). They are located approximately 35 km south of Brasilia, DF, Brazil (15° 51' S and 47° 63' W). The elevation is 1,100 m and slopes are < 10%. During the period from 1980 to 1992, mean annual temperature varied from 19.2 °C to 22.4 °C. Mean precipitation was 1482 mm distributed in two distinctive seasons, the wet season from October to March with 1257 mm and the dry season from April to September with 225 mm. Mean maximum relative humidity was 81% in December, and the mean minimum was 55% in August (File data from Estação Agroclimatológica do IBGE 1980-1992).

Vegetation in these Ecological Reserves is distributed in mosaics of community types described earlier, plus intermediate forms that were shaped by fire. In this study, four community types were investigated: campo limpo and campo sujo (already

described) and cerrado aberto and cerrado denso, both variants of cerrado *sensu stricto*. Cerrado aberto had a more open and less dense tree canopy compared to cerrado denso.

Methods

Aboveground vegetation and nutrient pools

Aboveground nutrient pools were divided into litter, woody debris, graminoids (dry and green), herbs (small dicots), shrubs (leaves and total), and trees. These were the main components partitioned to describe aboveground biomass of these communities (Chapter 2). Mass of C, N, and S was calculated utilizing plant nutrient concentrations from the same study area reported by Kauffman et al. (1994) (Appendix 4.1). To calculate nutrient pools, nutrient concentration in each component was multiplied by its respective biomass reported in Chapter 2. Some minor components in this study (e.g. litter and dicots in campo limpo, and shrubs and trees in campo sujo) were not included in the estimation of nutrient mass because nutrient concentration for these components were not provided by Kauffman et al. (1994). Nutrient mass of cerrado aberto and cerrado denso, were calculated according to the nutrient concentration of campo cerrado and cerrado *sensu stricto* of Kauffman et al. (1994). Nutrient concentration of wood debris for cerrado aberto and denso was that of cerrado *sensu stricto*. To determine nutrient mass concentration of trees, I used the concentration means from unpublished data (Dr. Kauffman in a pers. com.) (Appendix 4.2). After fire, the nutrient concentration and pools of residual biomass were calculated utilizing the same nutrient concentration applied for calculating nutrient mass before fire. I assumed that nutrient concentration in residual biomass did not change significantly due to fire. Ash nutrient

concentration for each fire was determined because the variability of individual fires influences the concentration and mass of nutrients in ash. Ash samples for nutrient analyses were the same as for ash mass determination (Chapter 2); five samples were collected for each community type. Carbon, N and S concentration in ash were analyzed using the induction furnace technique with Carlo Erba NA Series 1500.

Belowground nutrient pools

Belowground nutrient pools included root and soils to a depth of 2.00 m. Roots were classified on the basis of their diameter; size classes were ≤ 0.5 cm, 0.6-1.0 cm, 1.1-2.0 cm, 2.1-3.0 cm, and tubers. These were the same diameter classes used for root biomass quantification (Chapter 3). Nutrient concentration of five samples, randomly chosen, for each diameter class was determined for each community type. Nutrient mass in roots was calculated through multiplication of biomass in that diameter class by the mean nutrient concentration for each root diameter class. Soil nutrient concentration (N=5) was measured in each community type for the same depth intervals as root biomass quantification (i.e. 0-10 cm, 10-20 cm, 20-30 cm, 30-50 cm, 50-100, and 100-200 cm) (Chapter 3). Root samples were dried at 60 °C for 48 hours, and soil samples were air dried. Both were analyzed for C, N, and S concentration using a induction furnace method with Carlo Erba NA Series 1500. Soil mass was calculated from bulk density determined for the same depth intervals. After a monolith block was taken for root biomass studies, a bulk density sampler with a known ring volume was used to take samples from the wall of the soil pit. For sampling root biomass at 100 - 200 cm depth, an auger was used to a depth of 1.50 m. In the bottom of the hole, I collected a bulk density sample using the same sampler. Five samples were collected for each depth

interval for each community type. Samples were dried at 60 °C for 48 hours, weighed, and their bulk density calculated. (Appendix 4.3.).

Differences in nutrient concentration and nutrient pools among communities for aboveground and belowground pools were tested using Analysis of Variance (ANOVA). If assumptions of normality and equal variance were not assumed, log transformation were applied to the data. However, since data with log transformation had the same result as data without log transformation, results are presented without log transformation. If at least one community had concentrations or nutrient masses differing from other communities, the least significant test was applied to detect differences (p-value = 0.10) (Sokal and Rohlf 1981).

Results

Aboveground pools

Total aboveground biomass in Cerrado s.l. was 5,542 kg ha^{-1} for campo limpo, 7,523 kg ha^{-1} for campo sujo (excluding litter, dicot and tree components), 24,847 kg ha^{-1} for cerrado aberto, and 24,944 kg ha^{-1} for cerrado denso (Chapter 2, Table 2.1.).

Similar to aboveground biomass, nutrient pools of C, N, and S increased along the gradient from campo limpo to cerrado denso (Table 4.1.). Carbon pools ranged from 1,833 to 12,809 kg ha^{-1}, N pools from 15 to 185 kg ha^{-1}, and S pools from 1.7 to 15.2 kg ha^{-1} (Table 4.1.). There were no significant differences in the total nutrient pools between cerrado aberto and cerrado denso for any nutrient (Table 4.1.). Aboveground S pools in campo limpo and campo sujo were significantly different. However, no differences were detected between campo limpo and campo sujo for C and N (Table 4.1.). Woodland communities (cerrado aberto and cerrado denso) had at least 3-fold

Table 4. 1. Total nutrient pools (kg ha⁻¹) in Cerrado *sensu lato*, near Brasilia,DF, Brazil. Numbers are means ± standard error. Numbers in parenthesis are the relative proportion (%) of each component within aboveground, roots and soil pools.

	CARBON											
	campo limpo			campo sujo			cerrado aberto			cerrado denso		
ABOVE												
wd* <0.64	-			-			161 ± 25		(1)	148 ± 14		(1)
wd >0.64	-			-			796 ± 78		(7)	816 ± 104		(6)
litter	-			960 ± 157	a	(27)	2,572 ± 193	b	(21)	1,791 ± 138	c	(14)
dry graminoids	957 ± 66	a	(51)	1,602 ± 148	b	(44)	1,059 ± 103	a	(9)	676 ± 60	c	(5)
green graminoids	926 ± 67	ab	(49)	374 ± 45	b	(10)	177 ± 15	c	(1)	147 ± 12	c	(1)
dicot	-			701 ± 110		(19)	793 ± 88		(7)	855 ± 92		(7)
leaf-shrub	-			-			384 ± 39			216 ± 25		
total -shrub	-			-			3,216 ± 289	a	(26)	1,513 ± 197	b	(12)
trees	-			-			3,386 ± 956		(28)	6,863 ± 1345		(54)
total	1,833 ± 112	a		3,637 ± 413	a		12,160 ± 788	b		12,809 ± 1511	b	
ROOT(diameter class)												
<0.6 cm	4,270 ± 445	a	(56)	6,885 ± 434	b	(16)	9,092 ± 725	c	(40)	7,487 ± 1116	bc	(29)
0.6-1.0	439 ± 183	a	(6)	2,478 ± 568	b	(16)	3,795 ± 573	c	(17)	2,698 ± 486	bc	(11)
1.1-2.0	1,513 ± 947	a	(20)	2,866 ± 761	a	(19)	3,262 ± 728	a	(14)	5,475 ± 960		(22)
2.1-3.0				1,702 ± 867		(11)	1,506 ± 703		(6)	4,610 ± 1295		(18)
tuber	1,411 ± 672		(18)	1,158 ± 760		(8)	5,335 ± 1993		(23)	5,213 ± 2908		(20)
total	7,633 ± 1177	a		15,088 ± 2250	b		22,990 ± 3009	c		25,482 ± 4091	c	
SOIL(depth class)												
0-10	42,972 ± 1805	a	(17)	27,867 ± 2956	b	(13)	31,286 ± 1914.5	b	(12)	31,991 ± 869	b	(12)
10-20	36,493 ± 2602	a	(15)	20,980 ± 1580	b	(10)	25,620 ± 773.2	c	(10)	24,967 ± 622	b	(10)
20-30	26,615 ± 2785	a	(11)	20,080 ± 988	b	(10)	22,473 ± 965.9	b	(9)	23,052 ± 579	ab	(9)
30-50	27,347 ± 4828		(11)	21,757 ± 1060		(10)	25,352 ± 409.0		(10)	25,207 ± 667		(10)
50-100	44,726 ± 1829	a	(18)	45,140 ± 2531		(21)	53,356 ± 2164.4	b	(21)	55,415 ± 2861	b	(22)
100-200	67,833 ± 2278	a	(28)	74,951 ± 5378	a	(36)	98,905 ± 2728.0	b	(38)	94,418 ± 3236	b	(37)
total	245,986 ± 6069	a		210,774 ± 12436	b		256,992 ± 7331.1	a		255,050 ± 6775	a	
TOTAL SYSTEM	255,453			229,500			292,142			293,342		

*wd means wood debris. Different letters denote a significant difference (P ≤ 0.10) when testing carbon mass among the communities of Cerrado *sensu lato*, near Brasilia, DF, Brazil. The absence of letters denotes no statistical differences among communities. Dashes (-) denote that components were not found in the community.

Table 4.1. Continued

	campo limpo			campo sujo			cerrado aberto			cerrado denso		
NITROGEN												
ABOVE												
wd* < 0.64	-			-			1.6 ± 0.2		(1)	1.5 ± 0.1		(1)
wd > 0.64	-	-		-			5.3 ± 0.5		(3)	5.7 ± 0.7		(3)
litter	-			13.4 ± 2.2	a	(34)	35.7 ± 2.7	b	(22)	25.8 ± 2.0	c	(14)
dry graminoids	5.3 ± 0.4	ab	(35)	9.6 ± 0.9	c	(25)	6.9 ± 0.7	a	(4)	4.6 ± 0.4	b	(6)
green graminoids	9.8 ± 0.7	a	(65)	4.5 ± 0.5	b	(12)	2.4 ± 0.2	c	(2)	1.7 ± 0.1	c	(1)
dicot	-			11.3 ± 1.8		(29)	12.1 ± 1.3		(7)	11.7 ± 1.3		(6)
leaf-shrub	-			-			9.2 ± 0.9	a		4.4 ± 0.5	b	
total -shrub	-			-			44.5 ± 4.0	a	(27)	19.1 ± 2.5	b	(10)
trees	-			-			56.8 ± 16.0	a	(34)	115.2 ± 22.6	b	(62)
total	15.1 ± 0.9	a		38.9 ± 5.7	a		165.3 ± 12.4	b		185.3 ± 24.4	b	
ROOT(diameter class)												
< 0.6 cm	72.7 ± 28.1	a	(57)	82.3 ± 3.8	ab	(46)	128.5 ± 11.3	b	(40)	106.6 ± 13.8	b	(29)
0.6-1.0	10.6 ± 4.2	a	(8)	29.7 ± 5.2	b	(17)	55.3 ± 10.9	c	(17)	40.6 ± 8.1	bc	(11)
1.1-2.0	31.6 ± 26.6		(25)	32.9 ± 9.0		(19)	40.1 ± 10.7		(13)	82.8 ± 9.3		(22)
2.1-3.0	-			18.9 ± 11.2		(11)	21.9 ± 14.2		(7)	62.3 ± 21.9		(17)
tuber	12.4 ± 4.5		(10)	12.5 ± 6.3		(7)	74.7 ± 31.6		(23)	76.6 ± 31.5		(21)
total	127.4 ± 33.9	a		176.3 ± 23.1	a		320.5 ± 40.9	b		368.8 ± 51.2	b	
SOIL(depth class)												
0-10	2,676 ± 110.7	a	(15)	1,964 ± 262.9	b	(16)	1,903 ± 72.4	b	(12)	2,100 ± 62.1	b	(12)
10-20	2,401 ± 126.5	a	(14)	1,467 ± 121.7	b	(12)	1,712 ± 97.1	b	(10)	1,725 ± 71.4	b	(10)
20-30	1,911 ± 156.0	a	(11)	1,355 ± 110.7	b	(11)	1,528 ± 95.7	b	(9)	1,527 ± 98.2	b	(9)
30-50	2,120 ± 266.0	a	(12)	1,303 ± 45.6	b	(11)	1,586 ± 196.9	b	(10)	1,556 ± 103.3	b	(10)
50-100	3,590 ± 160.7	a	(20)	2,203 ± 100.3	b	(18)	3,229 ± 321.8	a	(21)	3,219 ± 365.0	a	(22)
100-200	5,022 ± 179.5		(28)	3,859 ± 405.3		(32)	4,735 ± 385.3		(38)	4,964 ± 373.9		(37)
total	17,720 ± 395.6	a		12,150 ± 863.4	b		14,694 ± 470.5	c		15,091 ± 904.7	c	
TOTAL SYSTEM	17,862			12,365			15,180			15,645		

*wd means wood debris. Different letters denote a significant difference (P ≤ 0.10) when testing nitorgen mass among the communities of Cerrado *sensu lato*, near Brasilia, DF, Brazil. The absence of letters denotes no satatiscal differences among communities. Dashes (-) denote that components were not found in the community.

Table 4.1. Continued

	campo limpo			campo sujo			cerrado aberto			cerrado denso		
							SULFUR					
ABOVE												
wd* < 0.64	-			-			0.1 ± 0.0		(1)	0.1 ± 0.0		(1)
wd > 0.64	-			-			0.5 ± 0.0		(3)	0.5 ± 0.1		(3)
litter	-			1.4 ± 0.2	a	(21)	4.1 ± 0.3	b	(27)	2.7 ± 0.2	c	(18)
dry graminoids	0.8 ± 0.1	a	(45)	1.2 ± 0.1	b	(17)	0.8 ± 0.1	a	(5)	0.5 ± 0.0	c	(4)
green graminoids	0.9 ± 0.1	a	(55)	0.5 ± 0.1	b	(8)	0.3 ± 0.0	c	(2)	0.2 ± 0.0	c	(1)
dicot	-			3.7 ± 0.6	a	(54)	1.3 ± 0.1	c	(9)	1.5 ± 0.2	b	(10)
leaf-shrub	-			-			1.0 ± 0.1	a		0.4 ± 0.1	b	
total -shrub	-			-			4.4 ± 0.4	a	(28)	1.8 ± 0.2	b	(12)
trees	-			-			3.8 ± 1.1	a	(25)	7.7 ± 1.5	b	(51)
total	1.7 ± 0.1	a		6.7 ± 0.9	b		15.3 ± 0.9			15.2 ± 1.7	c	
ROOT(diameter class)												
< 0.6 cm	4.8 ± 2.0		(59)	5.6 ± 0.4		(45)	7.1 ± 0.6		(42)	5.7 ± 0.4		(27)
0.6-1.0	0.5 ± 0.2	a	(6)	1.6 ± 0.3	b	(14)	2.7 ± 0.5	b	(16)	2.2 ± 0.5	b	(11)
1.1-2.0	1.9 ± 1.6		(24)	2.0 ± 0.5		(16)	1.8 ± 0.4		(11)	4.6 ± 0.4		(22)
2.1-3.0				2.1 ± 1.5		(17)	1.0 ± 0.5		(6)	3.4 ± 1.1		(16)
tuber	0.8 ± 0.3		(11)	1.0 ± 0.5		(8)	4.2 ± 1.5		(25)	5.1 ± 2.5		(24)
total	8.0 ± 2.5	a		12.2 ± 2.5	ab		16.7 ± 1.9	bc		21.0 ± 3.6	c	
SOIL(depth class)												
0-10	124.3 ± 5.9	a	(5)	138.4 ± 15.4	ab	(5)	308.0 ± 17.7	c	(8)	174.0 ± 24.3	b	(11)
10-20	134.0 ± 11.5	a	(5)	130.2 ± 26.7	a	(5)	202.3 ± 10.7	b	(5)	132.3 ± 15.1	a	(9)
20-30	131.1 ± 4.9	a	(5)	163.5 ± 17.2	a	(5)	198.1 ± 16.6	b	(5)	132.9 ± 10.8	a	(9)
30-50	183.3 ± 10.3	a	(7)	231.8 ± 29.7	a	(8)	322.6 ± 47.5	b	(9)	156.6 ± 16.3	a	(10)
50-100	755.7 ± 133.7	a	(29)	677.0 ± 12.7	a	(23)	761.1 ± 103.1	a	(21)	157.3 ± 11.6	b	(10)
100-200	1,301.1 ± 86.3	a	(49)	1,607.3 ± 211.5	ab	(54)	1,928.4 ± 265.6	b	(51)	776.5 ± 50.4	c	(51)
total	2,629.5 ± 175.1	a		2,948.3 ± 282.0	a		3,720.5 ± 403.1	b		1,529.6 ± 66.8	c	
	2,639.3			2,967.2			3,752.5			1,565.8		

*wd means wood debris. Different letters denote a significant difference (P ≤ 0.10) when testing sulfur mass among the communities of Cerrado *sensu lato*, near Brasilia, DF, Brazil. The absence of letters denotes no statistical differences among communities. Dashes (-) denote that components were not found in the community.

more aboveground total C mass than grassland communities (campo limpo and campo sujo); N mass was 4-fold more and S mass was 2-fold more. Nutrient pools in campo limpo and campo sujo were predominantly in graminoids. In contrast, in cerrado aberto and cerrado denso communities had the occurrence of shrubs and trees, which accounted for between 54% and 72% of their total nutrient pools.

Fine roots (≤ 0.5 cm) contributed the majority of nutrient mass in all communities (Table 4.1.). However, while in campo limpo more than 55 % of C, N, and S mass was in this diameter class, in cerrado denso only 29 % was presented in the fine roots. In cerrado denso, root nutrient mass was more evenly distributed among other diameter classes. Tubers of cerrado aberto and cerrado denso had higher nutrient pools than did and cerrado denso communities had the occurrence of shrubs and trees, which accounted for between 54% and 72% of their total nutrient pools.

Root nutrient concentration and mass

Nutrient concentration tended to be higher in tubers than in roots of all diameter classes, except in the campo limpo community, although statistically differences were not detected. For example, tuber N concentration in cerrado denso was 1.25 % while roots ≤ 0.5 cm and 0.6-1.0 cm in diameter had 0.71 %; 1.1-2.0 cm had 0.77 %; and 2.1-3.0 cm had 0.62 %. Carbon concentration in the roots of campo limpo tended to be lower than in campo sujo, cerrado aberto, and cerrado denso. On the other hand, N and S concentrations in the roots of campo limpo tended to be higher than in the other communities (Table 4.2.).

Table 4.2. Nutrient concentrations (%) of roots by diameter, and tubers along a vegetation gradient in Cerrado *sensu lato*, near Brasilia, DF, Brazil.

CARBON

	campo limpo		campo sujo		cerrado aberto		cerrado denso	
<0.6	46.74 ± 1.18	a	49.92 ± 0.42	b	48.78 ± 0.05	b	48.7 ± 0.12	b
0.6-1.0	44.66 ± 1.27	a	50.19 ± 0.55	b	49.05 ± 0.43	bc	48.26 ± 0.16	c
1.1-2.0	48.70 ± 1.51	ac	50.89 ± 0.70	b	49.70 ± 0.11	bc	47.07 ± 0.22	a
2.1-3.0	-		51.82 ± 0.31	a	50.03 ± 0.58	b	47.97 ± 0.33	c
tuber	47.11 ± 1.03		48.48 ± 0.90		49.98 ± 1.03		47.62 ± 0.69	

NITROGEN

	campo limpo		campo sujo		cerrado aberto		cerrado denso	
<0.6	0.75 ± 0.24		0.60 ± 0.02		0.68 ± 0.02		0.71 ± 0.06	
0.6-1.0	1.13 ± 0.16	a	0.63 ± 0.06	b	0.69 ± 0.06	b	0.71 ± 0.75	b
1.1-2.0	0.71 ± 0.27		0.56 ± 0.03		0.57 ± 0.05		0.77 ± 0.13	
2.1-3.0	-		0.63 ± 0.34		0.63 ± 0.24		0.62 ± 0.10	
tuber	0.56 ± 0.11		0.68 ± 0.19		0.72 ± 0.14		1.25 ± 0.45	

SULFUR

	campo limpo	campo sujo	cerrado aberto	cerrado denso
<0.6	0.049 ± 0.017	0.040 ± 0.002	0.038 ± 0.001	0.039 ± 0.004
0.6-1.0	0.059 ± 0.013	0.036 ± 0.006	0.034 ± 0.003	0.039 ± 0.060
1.1-2.0	0.044 ± 0.015	0.035 ± 0.003	0.026 ± 0.017	0.042 ± 0.004
2.1-3.0	-	0.071 ± 0.051	0.032 ± 0.003	0.033 ± 0.005
tuber	0.04 ± 0.013	0.062 ± 0.028	0.042 ± 0.050	0.081 ± 0.032

Numbers are means followed by standard error. Different letters denote a significant difference (P-value < 0.10) in concentration when testing among communities using LSD test. No letters denotes no statistically differences among comunity types.

Root biomass in Cerrado *sensu lato* was 16,317 kg ha^{-1} in campo limpo, 30,083 kg ha^{-1} in campo sujo, 46,584 kg ha^{-1} in cerrado aberto, and 52,908 kg ha^{-1} in cerrado denso (Chapter 3, Table 3.1.). Carbon mass ranged from 7,633 kg ha^{-1} in campo limpo to 25,482 kg ha^{-1} in cerrado denso, the N pool ranged from 127 kg ha^{-1} in campo limpo to 369 kg ha^{-1} in cerrado denso, and the S pool was 8 kg ha^{-1} in campo limpo to 21 kg ha^{-1} in cerrado denso (Table 4.1.). Total C, N, and S pools in the roots of cerrado aberto were not significantly different from those of cerrado denso, while the total C pool in campo limpo was significantly different from that of campo sujo, but the N pools or S pools were not. Fine roots (≤ 0.5 cm) contributed the majority of nutrient mass in all communities (Table 4.1.). However, while fine roots contained 55 % of C, N and S mass in campo limpo, in cerrado denso only 29 % was present in fine roots. In cerrado denso, root nutrient mass was more evenly distributed among other diameter classes. Tubers of cerrado aberto and cerrado denso had higher nutrient pools than did tubers from campo limpo and campo sujo. Carbon mass in tubers was at least 1.5-times greater in woodlands than in grasslands. Nitrogen mass in tubers was approximately in 1.8-times greater in woodland; and S mass in tubers was 1.4-times greater woodlands than in grasslands.

Soil nutrient concentration and mass

Soil nutrient concentration was distributed differently among depths (Table 4.3.). Carbon and N were highest at surface soils and decreased with depth up to 2.00 m. Campo limpo had the highest C and N concentration among the communities sampled, and there was a slight increase in concentration of C and N from campo sujo to cerrado denso (not statistically significant). Sulfur concentration in soils of campo limpo, campo sujo, and cerrado aberto did not vary among depths. For example S concentrations in

Table 4.3. Concentration (%) of carbon, nitrogen, and sulfur in soils to depth of 2 m along a vegetation gradient of Cerrado *sensu lato*, near Brasilia, DF, Brazil.

CARBON

soil depth(cm)	campo limpo	campo sujo	cerrado aberto	cerrado denso
0-10	4.63 ± 0.087 a	3.00 ± 0.318 b	3.37 ± 0.092 b	3.44 ± 0.042 b
10-20	3.64 ± 0.116 a	2.09 ± 0.158 b	2.55 ± 0.034 b	2.49 ± 0.028 b
20-30	2.37 ± 0.111	1.79 ± 0.088	2.01 ± 0.039	2.06 ± 0.023
30-50	1.61 ± 0.127	1.28 ± 0.062	1.49 ± 0.011	1.48 ± 0.018
50-100	0.98 ± 0.018 a	0.99 ± 0.056 a	1.17 ± 0.021 b	1.22 ± 0.028 b
100-200	0.66 ± 0.010	0.73 ± 0.053	0.97 ± 0.012	0.92 ± 0.014

NITROGEN

soil depth(cm)	campo limpo	campo sujo	cerrado aberto	cerrado denso
0-10	0.288 ± 0.005 a	0.211 ± 0.028 b	0.205 ± 0.003 b	0.226 ± 0.003 b
10-20	0.239 ± 0.006 a	0.146 ± 0.012 b	0.171 ± 0.004 b	0.172 ± 0.003 b
20-30	0.171 ± 0.006 a	0.121 ± 0.010 b	0.136 ± 0.004 b	0.136 ± 0.004 b
30-50	0.124 ± 0.007 a	0.077 ± 0.003 b	0.093 ± 0.005 b	0.091 ± 0.003 b
50-100	0.079 ± 0.002 a	0.048 ± 0.002 b	0.071 ± 0.003 a	0.071 ± 0.004 a
100-200	0.049 ± 0.001	0.038 ± 0.004	0.046 ± 0.002	0.049 ± 0.002

SULFUR

soil depth(cm)	campo limpo	campo sujo	cerrado aberto	cerrado denso
0-10	0.013 ± 0.0003 a	0.015 ± 0.0017 ab	0.033 ± 0.0009 c	0.019 ± 0.0012 b
10-20	0.013 ± 0.0005 a	0.013 ± 0.0027 a	0.020 ± 0.0005 b	0.013 ± 0.0007 a
20-30	0.012 ± 0.0002 a	0.015 ± 0.0015 a	0.018 ± 0.0007 b	0.012 ± 0.0004 a
30-50	0.011 ± 0.0003 ab	0.014 ± 0.0017 b	0.019 ± 0.0012 c	0.009 ± 0.0004 a
50-100	0.017 ± 0.0013 a	0.015 ± 0.0003 a	0.017 ± 0.0010 a	0.009 ± 0.0003 b
100-200	0.013 ± 0.0004 a	0.016 ± 0.0021 ab	0.019 ± 0.0012 b	0.008 ± 0.0002 c

Numbers are means followed by standard error. Different letters denote significant differences (P-value ≤ 0.10) when testing among communities using LSD test.

campo sujo soils through the 2.00 m depth, were between 0.013 and 0.016 %. In contrast, S concentrations in cerrado denso soils followed the same pattern as C and N, decreasing from surface to the deep areas of the soil. Sulfur concentrations in the upper 10 cm of the soil increased from campo limpo to cerrado aberto (0.013 % to 0.033 %), but declined in cerrado denso (Table 4.3.).

Along the Cerrado vegetation gradient, total C soil pool increased from 210,775 kg ha^{-1} to 256,992 kg ha^{-1} (Table 4.1.). Campo sujo had the lowest soil C mass and was the only community that differed significantly from the others (Table 4.1.). Campo limpo had the highest amount of total N in soil; from campo sujo to cerrado denso, total N increased from 12,150 kg ha^{-1} to 15,091 kg ha^{-1}. Total soil pool of S increased from campo limpo to cerrado aberto. However, total S pools were the lowest in cerrado denso.

Surface soil layers (0-10, 10-20, and 20-30 cm) of campo limpo tended to have a significantly higher C mass than other communities. For each depth interval up to 50 cm, soil N mass in campo limpo was significantly higher than campo sujo, cerrado aberto or cerrado denso. Cerrado aberto had the highest soil S pools for each depth interval. At 0-10 cm interval, cerrado aberto S pool was 308 kg ha^{-1}; the same soil interval at cerrado denso had 174 kg ha^{-1}.

Carbon and N mass decreased with soil depth (Table 4.1.). Carbon and N mass in the first meter of soil contributed to more than 62 % of the total soil pool in Cerrado s.l.. Campo limpo in the first meter contained 70 % of the total soil C and 71 % of the total soil N. In contrast, S mass was equally distributed throughout the soil profile. The upper 1.00 m of the soil profile comprised 51 %, 46 %, 49 % and 49 %, respectively, of the total mass in campo limpo, campo sujo, cerrado aberto and cerrado denso (Table 4.1.).

Total ecosystem C, N, and S pool

Total ecosystem nutrient pools (aboveground, root, and soil) did not have the same variability among communities as did aboveground and root nutrient pools. Total ecosystem pool ranged from 229,500 to 293,341 kg ha^{-1} of C, 12,450 to 17,720 kg ha^{-1} of N, and 1,566 to 3,753 kg ha^{-1} of S in campo limpo and cerrado denso respectively (Table 4.1.). Soil pools accounted for more than 86 % of all nutrients measured in all communities while roots comprised 0.3 to 8.7 %, and aboveground contained only 0.1 to 4.4 % of the total ecosystem pool (Figure 4.1.).

In terms of plant nutrient pools, most of the nutrient mass was in belowground components (Figure 4.2.). Root N and C pools were more than 80 % of the total aboveground and root pools combined for grasslands and more than 65 % of these combined pools for woodlands. Sulfur root pool in campo limpo also had 80 % of its total plant pool, but in campo sujo it dropped to 63 %. Cerrado aberto and cerrado denso tended to accumulate more S in the aboveground pool than did the other communities, with roots accounting for 53 % and 58 % respectively. Consequently, root:shoot ratios of nutrients were in generally higher for C and N than for S (Figure 4.2.). Carbon root:shoot ratio was approximately 4 in grasslands and 2 in woodlands. Nitrogen root:shoot ratio pool in campo limpo was 8, but decreased to 2 in woodlands. Sulfur root:shoot ratio was generally half of N root:shoot for all communities.

Fire effects on nutrients

Aboveground nutrient pools after fire included residual uncombusted material such as green graminoids, dicots, stems from shrubs, trees, and ash. Cerrado aberto and
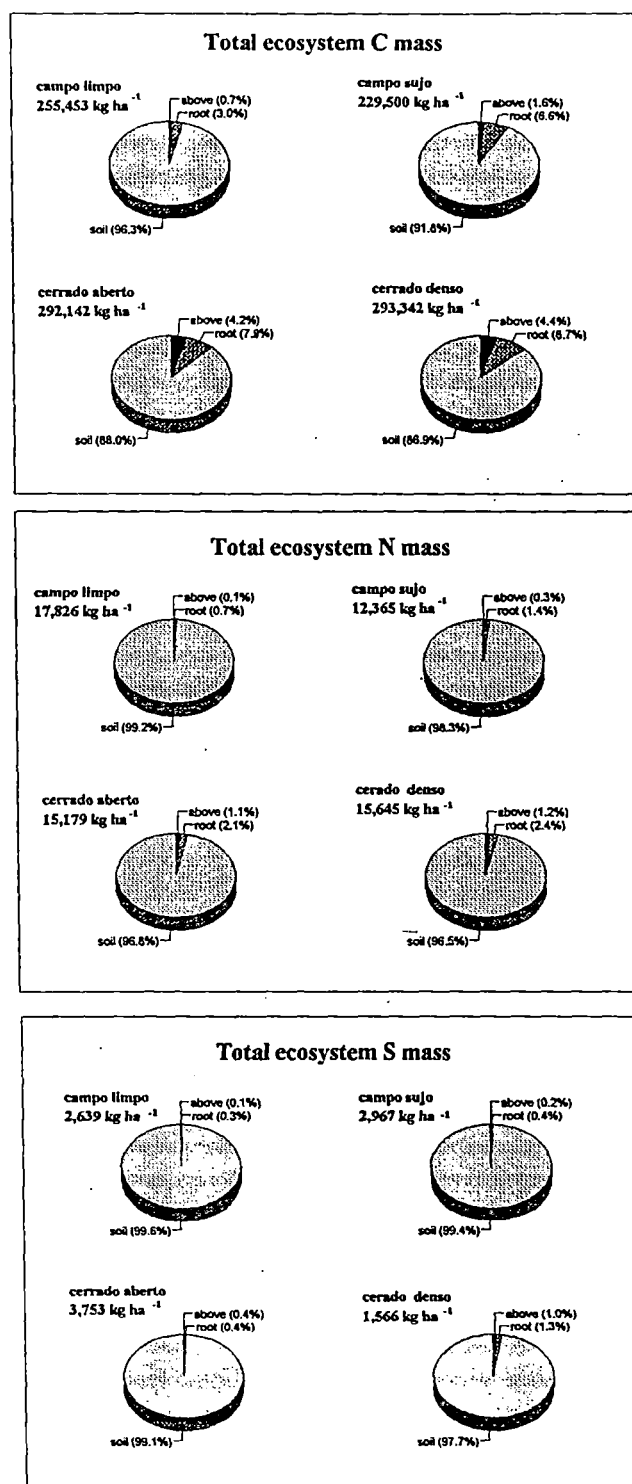
Figure 4.1. Relative proportion of carbon, nitrogen, and sulfur of the total ecosystem pool (above, root and soil) in Cerrado gradient, near Brasilia, DF, Brazil.
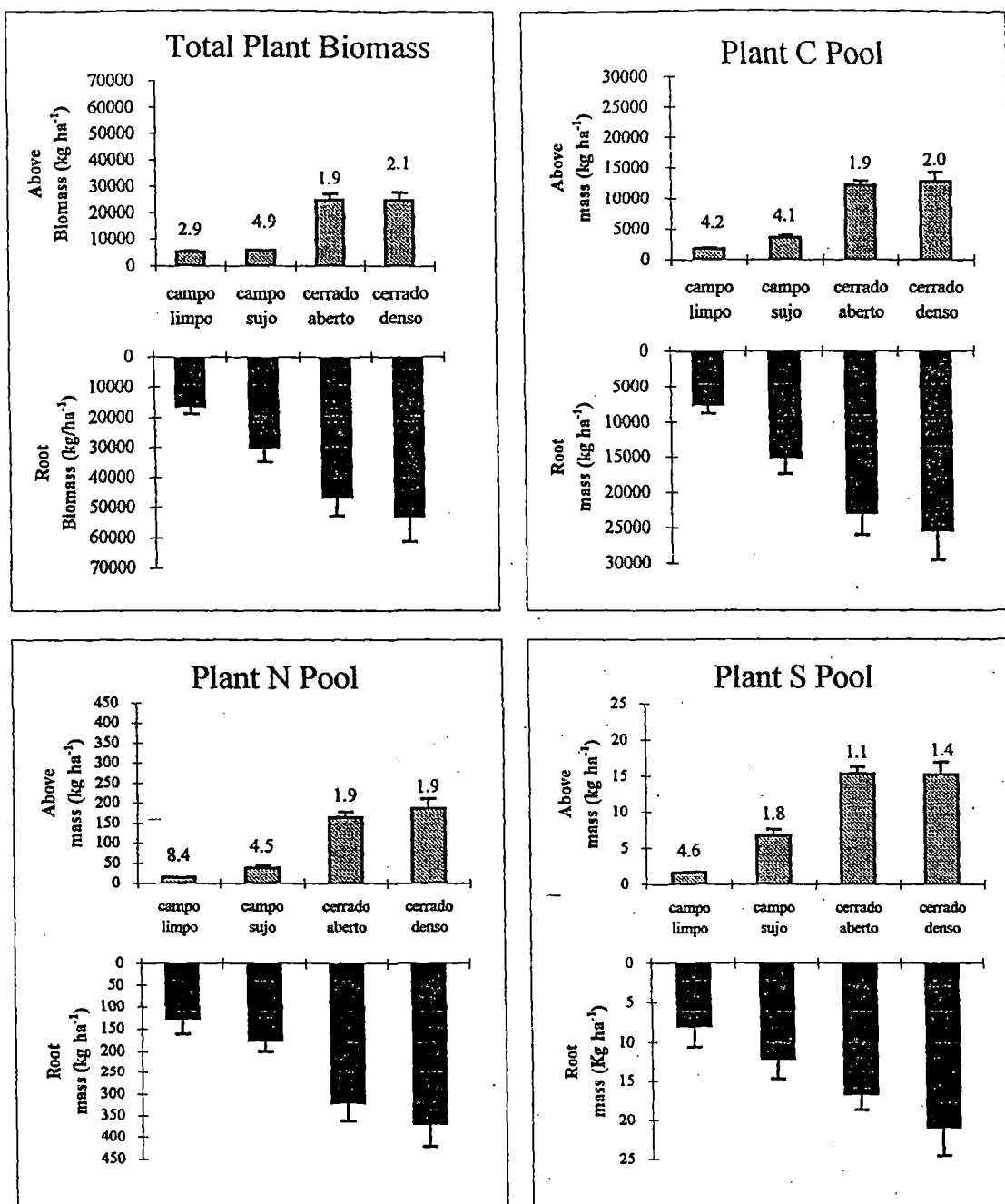
Figure 4.2. Comparison of aboveground biomass and root pools of carbon, nitrogen, and sulfur in Cerrado *sensu lato*. Bars are standard errors, and values above them are root:shoot ratio of biomass and nutrient masses.

cerrado denso had the highest mass of nutrients left on the ground after fire. Carbon nutrient pool after fire varied from 159 to 9,425 kg ha^{-1}, N nutrient pool after fire ranged from 2.2 kg ha^{-1}in campo limpo to 152 kg ha^{-1}in cerrado denso, and S pool after fire was between 0.1 kg ha^{-1}and 10.1 kg ha^{-1} in campo limpo and cerrado denso respectively (Figure 4.3.).

Nutrient concentration in ash increased from grasslands (20.6 % for C; 0.37 % for N, and 0.032 % for S) to woodlands; cerrado aberto had a slightly higher ash nutrient concentration (40.8 % for C, 1.15 % for N, and 0.057 % for S) than cerrado denso (Table 4. 4.A). Ash nutrient mass in cerrado aberto was greater than in other communities for all nutrients (Table 4. 4.B). Ash C mass in cerrado aberto was 928 kg ha^{-1}; N was 26.2 kg ha^{-1}; and S, 1.3 kg ha^{-1}. However, the percentage of loss by volatilization in cerrado aberto was the lowest of all communities, i.e. 81.6 % C, 34.6 % N, and 80.6 % S (Table 4.4.B). In contrast, campo limpo had the highest loss by volatilization of C (95.2 %), N (89.5 %), and S (91.4 %).

In terms of the total ecosystem, losses of nutrients by volatilization were minimal. Carbon losses in campo limpo were 0.67 %, in campo sujo 1.58 %, in cerrado aberto 1.61 %; and in cerrado denso 1.08 %. Nitrogen losses were 0.07 % for campo limpo, 0.20 % for campo sujo, 0.11 % for cerrado aberto, and 0.13 % for cerrado denso. Losses of S in campo limpo were 0.05 %, in campo sujo 0.19 %, in cerrado aberto 0.15 %, and in cerrado denso 0.25 %.
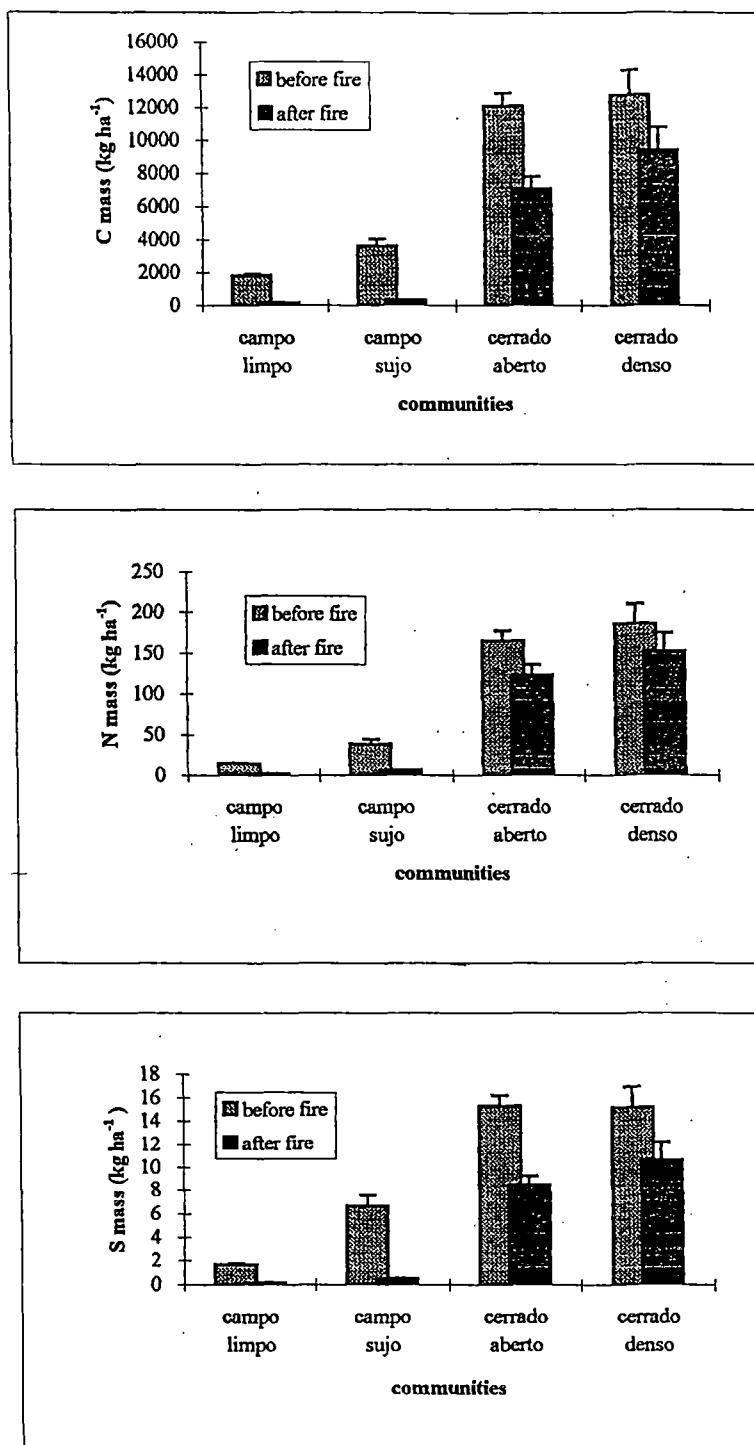
Figure 4.3. Aboveground carbon, nitrogen, and sulfur mass (kg ha^{-1}) in plant communities along a vegetation gradient in Cerrado *sensu lato* before and after fire, Brasilia, DF, Brazil.

Table 4.4. Nutrient ash concentration (%) (A), and total nutrient losses (B) via particulate transport and through volatilization (kg ha^{-1}) during fires along a vegetation gradient of Cerrado *sensu lato*, near Brasilia, DF, Brazil.

(A)

	campo limpo	campo sujo	cerrado aberto	cerrado denso
Carbon	20.65 ± 1.18	24.66 ± 1.25	40.83 ± 0.66	40.66 ± 1.34
Nitrogen	0.34 ± 0.03	0.55 ± 0.04	1.15 ± 0.03	1.00 ± 0.02
Sulfur	0.03 ± 0.00	0.04 ± 0.00	0.06 ± 0.00	0.05 ± 0.00

(B)

CARBON			
campo limpo	campo sujo	cerrado aberto	cerrado denso

	campo limpo	campo sujo	cerrado aberto	cerrado denso
total site loss	1724.5 ± 117.4	3637.4 ± 413.5	5059.3 ± 175.4	3365.7 ± 309.3
particulate	83.1 ± 6.9	316.4 ± 28.3	928.3 ± 124.8	605.1 ± 59.7
volatilization	1641.4 ± 113.7	3321.0 ± 413.5	4131.0 ± 219.5	2760.6 ± 291.2
% loss volatilization	95.2 ± 0.4	90.9 ± 1.3	81.6 ± 2.6	81.7 ± 2.1

NITROGEN			
campo limpo	campo sujo	cerrado aberto	cerrado denso

	campo limpo	campo sujo	cerrado aberto	cerrado denso
total site loss	12.9 ± 0.9	31.5 ± 5.8	42.0 ± 3.9	34.1 ± 2.2
particulate	1.4 ± 0.1	7.1 ± 0.6	26.2 ± 3.5	14.9 ± 1.5
volatilization	11.6 ± 0.9	24.4 ± 5.9	15.8 ± 6.6	19.2 ± 2.1
% loss volatilization	89.5 ± 0.8	74.7 ± 5.3	34.6 ± 12.8	56.2 ± 3.9

SULFUR			
campo limpo	campo sujo	cerrado aberto	cerrado denso

	campo limpo	campo sujo	cerrado aberto	cerrado denso
total site loss	1.5 ± 0.1	6.2 ± 0.9	6.8 ± 0.4	4.6 ± 0.4
particulate	0.1 ± 0.0	0.5 ± 0.0	1.3 ± 0.2	0.7 ± 0.1
volatilization	1.4 ± 0.1	5.7 ± 0.9	5.5 ± 0.4	3.9 ± 0.4
% loss volatilization	91.4 ± 0.7	91.2 ± 1.8	80.6 ± 2.8	84.3 ± 1.5

Discussion

Aboveground pools

The increasing mass of aboveground nutrient pools along the gradient campo limpo to cerrado denso was associated with an increase in aboveground biomass (Chapter 2). The different structure of plant communities resulted in differences in total nutrient storage and within components of each community. The dominance of shrubs and trees in cerrado aberto and cerrado denso resulted in significant aboveground pools that did not exist in grasslands. This diversity of vegetation structure may influence the fire effects on the dynamic of nutrient pools.

Nutrient dynamics in Cerrado s.l. are poorly studied (Pereira 1982). Nitrogen mineralization in Cerrado is higher in the rainy season than during the dry season. Microbial activity increases with the higher soil humidity, increasing the rate of decomposition, and consequently the release of nutrients (Suhett et al. 1987). In the interval between natural fires in tropical savannas in general, decomposition although slow may be significant in increasing nutrient availability, particularly at the onset of the rainy season. (Frost and Robertson 1985, Swift et al. 1979). Therefore, the nutrient content in dead material (woody debris, litter and dry graminoids, and dead roots) is the primary source of plant available nutrients via decomposition (Vitousek and Sanford 1986). When fires occur in this ecosystem, most of the accumulated dead material is consumed (Chapter 2) and nutrients are released. In this study, dead material comprised the second highest relative proportion of the nutrient pool (after trees) (Table 4. 1.). After fire, most of these nutrients may be returned to the same site via ash deposition.

Few studies in Cerrado s.l. have investigated nutrient pools in aboveground biomass. Nitrogen and sulfur mass in the ground layer biomass (excluding shrubs and

trees) ranges from 12.0 to 32.5 kg ha^{-1} and 2.6 to 6.8 kg ha^{-1}, respectively, in campo cerrado (Pivello and Coutinho 1992). These values are low compared to nutrient pools of the ground layer in cerrado aberto (64 kg ha^{-1} of N and 7.1 kg ha^{-1} of S) or cerrado denso (51.0 kg ha^{-1} of N and 5.7 kg ha^{-1} of S) of this study. The difference between literature values and those reported here are due to different methodologies used. I included materials from shrubs and trees in the litter component, and also quantified woody debris. For the ground layer of campo sujo, Batmanian and Haridasan (1985) reported a mass of 24 kg ha^{-1} of N for unburned area and 15 kg ha^{-1} of N for burned area. These values are also low compared to the 39 kg ha^{-1} measured in this study.

Carbon, N, and S mass of fuel of Cerrado s.l. were quantified by Kauffman et al. (1994). They reported nutrient pools of the fuel load to be approximately 3,350 kg ha^{-1} of C for grasslands and 4,500 kg ha^{-1} of C for woodlands. Nitrogen fuel load pool estimations is 25 kg ha^{-1} and 49 kg ha^{-1} for grassland and woodland, respectively. Sulfur fuel load is 3.7 kg ha^{-1} in grasslands and 5.6 kg ha^{-1} in woodland. The fuel load found in this study is in the range of those reported values. Fuel load in campo limpo and campo sujo for C, N, and S were the same as total nutrient pool because all components in these communities were very susceptible to fire. Cerrado aberto and cerrado denso had 5,942 kg ha^{-1} and 4,626 kg ha^{-1} of C, and 72 kg ha^{-1} and 55 kg ha^{-1} of N, respectively. Sulfur fuel load was 8 kg ha^{-1} for cerrado aberto and 10 kg ha^{-1} for cerrado denso.

Aboveground carbon, nitrogen, and sulfur pools in Cerrado s.l. were very low compared with either tropical rain forest or tropical dry forest. In the Brazilian Amazon forest, C, N, and S aboveground pools range from 148 to 218 Mg ha^{-1} of C, 1,401 to 2,327 kg ha^{-1} of N, and 251 to 392 kg ha^{-1} of S (Kauffman et al. 1995). In Amazon state, Klinge (1976) found 2,430 kg ha^{-1} of N in the aboveground biomass of tropical rain forest. In contrast, aboveground pools in this study were 13 Mg ha^{-1} of C, 185 kg ha^{-1} of N, and 15.2 kg ha^{-1} of S in the cerrado denso community, which had the highest nutrient pool in Cerrado s.l.. The Brazilian tropical dry forest, (known as caatinga) also had

larger aboveground nutrient pools than Cerrado s.l.. The aboveground C pool in tropical dry forest is 34 Mg ha^{-1}, and aboveground N pool is 538 kg ha^{-1}(Kauffman et al. 1993). In addition , tropical dry forest in Puerto Rico has 368 kg ha^{-1} of N in the living parts of aboveground biomass (Lugo and Murphy 1986).

Root nutrient concentration and mass

Fine roots were expected to have the highest nutrient concentration, since their function is water and nutrient absorption, while the function of coarse roots is to conduct water, to support the plant and to store water and nutrients (Kerfoot 1963). The absence of a pattern such as the smaller the diameter the higher the nutrient concentration could be due to the diversity of species composition with variability in nutrient concentrations (Edwards and Grubb 1982),.or to the contamination of fine roots by mineral soil and residual mycorrhiza that remained in the sample (Berish 1982).

Higher concentration of nutrients in tubers may be related to the occurrence of xylopodium (Chapter 3). In earlier studies, the function of these subterranean organs was believed to be water storage (Rawtscher and Rachid 1946 cited in Rizzini and Heringer 1961). However, more recently, Coutinho (1978c) demonstrated that water content in xylopodium was relatively low and constant throughout the year, while nutrient concentration was high, but variable. Peak of N concentrations in tubers of *Lantana montevidensis* (Verbenaceae) and *Isostigma peucedanifolium*, typical species of Cerrado s.l., were 1.9 % and 1.0 %, respectively. I found a range of 0.56 % to 1.23 % for N for the tubers measured in this study (Table 4.2.).

Prior to this study, no data were available for root nutrient pools in Cerrado s.l., and only a few studies of root nutrient pools had been reported for other tropical ecosystems (Klinge 1975, 1976, Edwards and Grubb 1982, Jordan et al. 1982, Lugo and

Murphy 1986). In tropical dry forest, root N pool is 546 kg ha^{-1} to a depth of 0.85 m

(Lugo and Murphy 1986). For tropical moist forest in the Brazilian Amazon, root N pool

is 404 kg ha^{-1} to a depth of 0.90 m (Klinge 1975). These amounts are larger than those

found for Cerrado s.l. in this study. Here, N mass in roots up to 2.00 m deep ranged from

127 kg ha^{-1} in campo limpo to 369 kg ha^{-1} in cerrado denso. However, N mass in these

roots of grassland communities comprised 80 % of phytomass nitrogen pool

(aboveground and root), and 65 % in woodlands. In contrast, roots of tropical dry forest

stored 45 % of the total plant N pool, while roots in tropical moist forest comprise only

19 % the total plant N pool (Klinge 1975, Lugo and Murphy 1986).

The distribution of nutrient masses among root diameters and tubers was more

diversified in cerrado denso than in campo limpo. This is likely due to the increase of

plant structural diversity in the cerrado denso community. Campo limpo and campo sujo

still had tubers, which were probably from herbs. The nutrient masses in tubers of

grasslands were lower because tuber biomass and concentration of nutrients were lower

in these communities .

Carbon pools in tropical ecosystems have received more attention recently

because of increases in atmospheric CO_2 and the potential role of these ecosystems as a

source. Although root biomass may constitute a high portion of C storage, studies have

neglected this pool because there is no immediate or readily observable release of C from

belowground when land is cleared and burned (Brown and Lugo 1993). However, when

a natural ecosystem is cut and burned for agricultural conversion, nutrient losses occur

not only from the direct losses of fire, but also from erosion and release via microbial

decomposition of dead roots (Vitousek 1983). Moreover, fine roots comprised 29 to

56 % of the total root mass (Chapter 2). After fire, this component of the root pool

would be expected to disappear rapidly via decomposition.

Most of the carbon allocated and stored in roots may be used under conditions of

stress such as drought, following fire or excessive grazing (Mooney 1972). This

adaptation facilitates the existence of Cerrado vegetation in a nutrient-poor soils with frequent fires.

Soil nutrient concentration and mass

The higher concentration of C and N nutrients located in the upper horizons of the soil profile is likely related to higher concentrations of organic matter. Since decomposition results in deposition of organic residues on the soil surface, organic matter tends to accumulate in upper horizons and decrease with depth (Stevenson 1986, Brady 1990). However, S concentration in this study did not decrease as C and N did; except in cerrado denso. In weathered soils, such as in the Cerrado, the abundance of oxides of Fe and Al tend to adsorb SO_4^{-2} particularly at greater depths where the pH is suppose to higher (Barrow 1960, Couto and Ritchey 1987, Schlesinger 1991).

Campo limpo communities are associated with hydromorphic soils, which are poorly drained (Haridasan 1990), with medium to high clay contents of low activity, low pH, with a high concentration of aluminum (Furley and Ratter 1988). High water content and poor aeration may reduce the rate of decay, thereby, accumulating organic matter, which in turn may contribute to the higher concentration of total C and total N in the soil (Stevenson 1986, Brady 1990). In contrast, campo sujo, campo cerrado, and cerrado s.s. are associated with Oxisols (Haridasan 1990), which are deep, weathered, porous, and sometimes associated with surface organic matter (Furley and Ratter 1988). Since these soils are more favorable to the decomposition than are hydromorphic soils, oxidation of nutrients are faster and part of the nutrient readily available to plants. Nutrient concentration from campo sujo to cerrado s.s. has been discussed by Goodland and Pollard (1973). They found an increase in nutrient concentrations from campo sujo to cerrado s.s.. Lower sulfur concentration in campo limpo may be related with the

anaerobic soil conditions for at least part of the year. Under these conditions, decomposition is slow, and produces different final products because different microorganisms are involved. Sulfur in gaseous form (H_2S) is one of the final products that is lost to the atmosphere (Stevenson 1986), possibly accounting for lower soil S concentration in campo limpo.

Pools of N in campo limpo soils were the highest due to higher N concentration in these communities. Moreover, bulk density in campo limpo was also one of the highest, especially in the first 0.30 m of the soil. Carbon and N pools decreased with depth as a function of lower nutrient concentration and lower soil bulk density (Appendix 4.3). The higher mass of S in the deep soil (100-200 cm), which was approximately 50 % of total S soil mass, was due to the higher concentration of S discussed before.

Although carbon stocks in soil have been reported as three to four times that of the living vegetation (Schlesinger 1990), I found C soil pool to a depth to 0.10 m to be 2 to 23 times more than aboveground biomass. The soil C pool in tropical rain forests in the states of Pará and Rondonia, in Brazil are estimated between 28 Mg ha^{-1} and 30 Mg ha^{-1} up to 10 cm in depth, respectively, or 11 to 17 % of the soil and aboveground combined (Kauffman et al. 1995). In the first 10 cm of Cerrado s.l. soils, C pool was 43 Mg ha^{-1} for campo limpo, 28 Mg ha^{-1} for campo sujo, 31 Mg ha^{-1} for cerrado aberto, and 32 Mg ha^{-1} for cerrado denso. Although the range of the soil C pool in Cerrado s.l. was similar to that reported for tropical rain forest (except for campo limpo), this top 10 cm of soil C corresponded to 95 % to 98 % of Cerrado s.l. aboveground biomass and soil combined. Considering that all these stored C is in balance with natural losses in the system (Perry et al. 1991), deforestation of Cerrado for agricultural purpose may release all these C by accelerating decomposition of organic matter in the soil, which will increase CO_2 in the atmosphere.

Fire effects on nutrient pools

Fire influences nutrient cycles by changing nutrient forms, nutrient distribution, and the mass of nutrients in the ecosystem (McNabb and Cromack Jr. 1990). The magnitude of these transformations depend upon fire intensity, fire duration, biomass nutrient content, and its consumption by fire (Frost and Robertson 1985), which in turn are related to vegetation structure. Woodlands had the highest masses of nutrients remaining after fire, most of which were bounded in unburned trees and shrubs. In contrast, campo limpo and campo sujo containing very combustible material, had low aboveground pools after fire.

High percentages of C, N, and S are lost via volatilization because they have low temperatures of volatilization (Kauffman et al.1992). Nitrogen volatilizes at approximately 400 °C, which is lower than most fire temperatures registered for Cerrado s. l. (Cesar 1980, Miranda et al. 1993). Biomass consumption was not as complete for woodlands as for grasslands, which may have contributed to a lower loss by volatilization in woodlands, particularly cerrado aberto, compared to other communities. In addition, ash mass was high for cerrado aberto (Chapter 2, Table 2.1.) and consequently a higher nutrient mass was deposited in ash. Low concentrations of C, N, and S found in ash mass relative to plant tissue concentrations for all communities suggest that volatilization of those nutrients was high (Table 4.4.). Campo limpo and campo sujo, which contained highly combustible components, had the highest losses of nutrients via volatilization, because more of the fuel bed was consumed during flaming combustion than in the cerrado *sensu stricto* community. These patterns of loss are similar to those reported by Kauffman et al. (1994) where volatilization and relative amount of loss were high.

Losses of nutrients associated with fire in the Brazilian rain forest were much higher than in Cerrado s.l.. In this study, losses of C by volatilization ranged from 1,641 to 4,131 kg ha^{-1}, losses of N ranged from 11.6 to 24.4 kg ha^{-1}, and losses of S were

between 1.4 to 5.7 kg ha^{-1}. Nutrient losses by fires in slashed primary tropical rain forest was between 58,000 and 112,000 kg ha^{-1}of C, 816 and 1,605 kg ha^{-1}of N, and 92 and 137 kg ha^{-1}of S (Kauffman et al.1995). These correspond to losses of 17 times more C, 24 times more N and 13 times more S in one burning of slashed primary tropical rain forest than losses in Cerrado s.l..

Total ecosystem C, N, and S pool

The distribution of the nutrient pool in Cerrado s.l., is unique relative to other tropical ecosystems. The high proportion of nutrient stocks found belowground is unlike that of moist and dry tropical forest. For example, total N pool in lowland tropical rain forest, in Brazil is 7,537 kg ha^{-1} 37 % of which is found in living aboveground biomass and litter, only 7 % in roots, and 56 % in soils (0-30 cm) (Klinge 1975 cited in Edwards and Grubb 1982). Tropical dry forest in Puerto Rico has 10,279 kg ha^{-1} of N in the total ecosystem. Aboveground biomass accounts for 6 %, roots 5 %, and soils 89 % (Lugo and Murphy 1986). Cerrado *sensu lato* in this study differed from the lowland tropical forest in the high amounts of nutrients in the soil (> 86 %), and much lower nutrient pool in the aboveground pool (0.1 to 8.7 %). Differences between this study and studies of tropical dry forest reported here is that, although tropical dry forest hold high nutrient pools in the soil, N is equally distributed in the phytomass; Cerrado *sensu lato* root biomass contributed to a greater pool of nutrients. This can be interpreted as an adaptative strategy for nutrient conservation in a nutrient-poor ecosystem with frequent fires.

Total ecosystem nutrient losses by fire were minimal because of the larger nutrient pools in the belowground part of the system. Belowground nutrient pools are well protected against disturbance such as fire. Soil is not strongly affected by fire because it has a low thermal conductivity. Slight increases in soil temperature were

detected only in the top first 5 cm of soils during fires in Cerrado s.l. (Coutinho 1978a, Miranda et al. 1993). Fire influences on soil nutrient pools were negligible because temperatures do not get high enough to volatilized C, N, or S.

Nutrient root:shoot ratio in Cerrado *sensu lato* indicates an efficient nutrient conservation from fires, except for S in the woodlands, where half of its S pool was subject to consumption by fire. This may account for the low S pool in the whole ecosystem.

Conclusion

Estimation of total C, N, and S pool and fire effects discussed in this study are not available elsewhere for Cerrado *sensu lato*. Here, aboveground, root and soil nutrient pools of four community types ranging from grasslands to woodland were quantified in area near Brasilia, DF, Brazil.

In contrast to other tropical ecosystems, aboveground biomass of Cerrado s.l. contributed only a small percentage ($\leq$ 4 %) of the total nutrient pools. Therefore, emissions of C, N and S to the atmosphere during burning were much lower than those reported for tropical rain or dry forest. In Cerrado s.l., the upper 10 cm of soil contains more than 90 % of the above and belowground nutrient pool. The large root mass contains for most of the nutrients stored in above and belowground plant biomass.

Deforestation in Cerrado s.l. may promote the release of a large mass of nutrients bounded in the root tissues and in the soil. The release of belowground C and other nutrients has not been included in the estimates of potential increases in atmosphere greenhouse gasses. Since, Cerrado s.l. has a large area in Brazil, and tropical savannas occupies 1530 million ha of the world land surface (Lanly 1982 cited in Andreae 1991), this potential sink or source of C and other nutrients can not be neglected.

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CHAPTER 5
CONCLUSION

Cerrado *sensu lato*, a tropical savanna, increased in aboveground and root biomass from grassland to woodland. These results suggested that each community type of the Cerrado gradient may be characterized by its biomass, in addition to the classification by tree density and basal area(Goodland and Pollard 1973), species composition (Eiten 1972) or plant physiognomy and structure(Eiten 1972, Coutinho,1976).

Roots accounted for most of the aboveground and root biomass combined, resulting in an ecosystem with a very high root:shoot ratio. Consequently, Cerrado *sensu lato* had a large pool of nutrients in its phytomass, even though nutrient concentrations were low. However, nutrient pools in the root are at least twice greater than aboveground pools for C and N.

Natural disturbances, such as fire, affect the ecosystem level by accelerating nutrient cycling and energy flow (White and Pickett 1985). Biomass consumption promotes nutrient volatilization, an emission of particulates that may contribute to the increase of CO_2 in the atmosphere as well the greenhouse effect.

Cerrado *sensu lato* vegetation has been characterized as very well adapted to fire (Coutinho, 1990). It has been described as a low severity fire regime with a fire return interval between 1-2 years for grasslands and 3-5 years for woodland (Eiten 1975, Pivello and Coutinho 1992).

This study indicates that nutrient pools are distributed in the total ecosystem of Cerrado *sensu lato* so that even with frequent fires, most of the nutrients remain in the ecosystem. The majority of nutrients are in the belowground systems (soil and root), which are not affected by fire. Consequently, emissions of C and other nutrients to the atmosphere from biomass burning in Cerrado *sensu lato* are much lower than in any

other tropical ecosystem of the same extended area. Nevertheless, considering the

extensive area of the world covered by tropical savannas and the frequency of fires, the

total amount of C and other nutrients released into the atmosphere by the many

individual fire may be substantial.

However, the low price of the land combined with the facilities of a mechanized

agriculture is changing the Cerrado *sensu lato* landscape in the central part of Brazil.

Monoculture of soybeans, rice, corn and eucalyptus is displacing the natural vegetation.

Deforestation of Cerrado *sensu lato* may promote a release of nutrients stored in the roots

and in the soil. Although, release of these nutrient through farming is not immediate and

much slower than nutrient release by biomass burning, nutrient losses is still

considerable. These losses need to be considered in the models of global climate change

to insure that predictions will be as accurate as possible.

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APPENDICES

Appendix 2.1. Experimental design for aboveground biomass established at each community type of Cerrado *sensu lato*, Brasilia, DF, Brazil. Total sample sizes were 32 for herbs and graminoids, wood debris = 24, and shrubs and trees = 16.

50 m

3 m

1 m

5 m

10 m

15 m
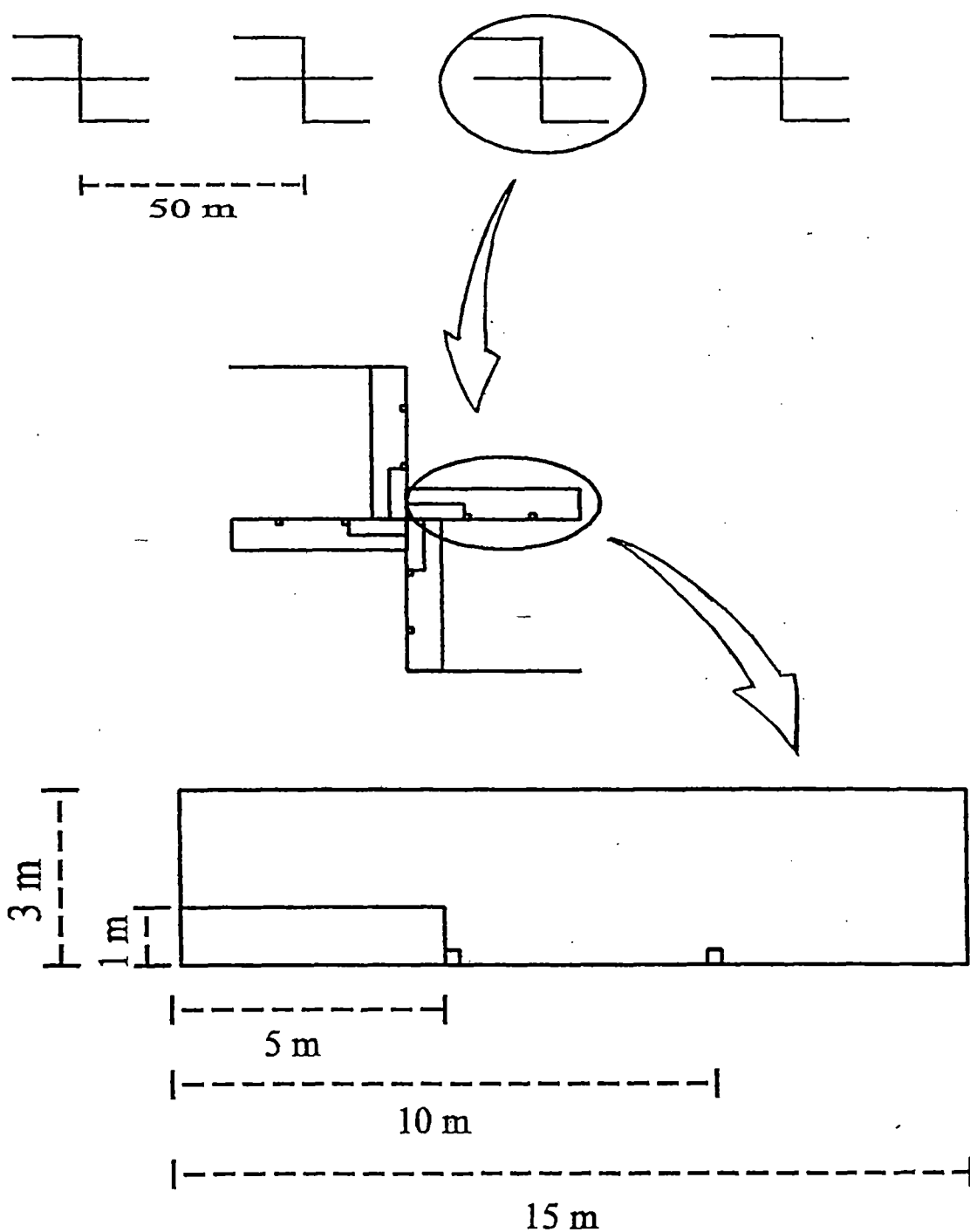
Appendix 2.2. Multiple regression equations to estimate shrub biomass of Cerrado *sensu lato* at IBGE Ecological Reserve, Brasilia,DF. (N=35).(Source: Dr. B. Kauffman personal communication)

Dependent variable	Equation	R^2	$AdjR^2$
Total biomass (g)	$721.404(\text{Volume } m^3)+8.4331(\text{diameter mm})$	.96	.95
Leaf biomass (g)	$24.7801(\text{Volume } m^3)+51.5634(\text{height m})$	.82	.80

Appendix 3.2. Fire descriptors: A = flame depth, B = flame height, C = flame length and ϕ = flame angle.
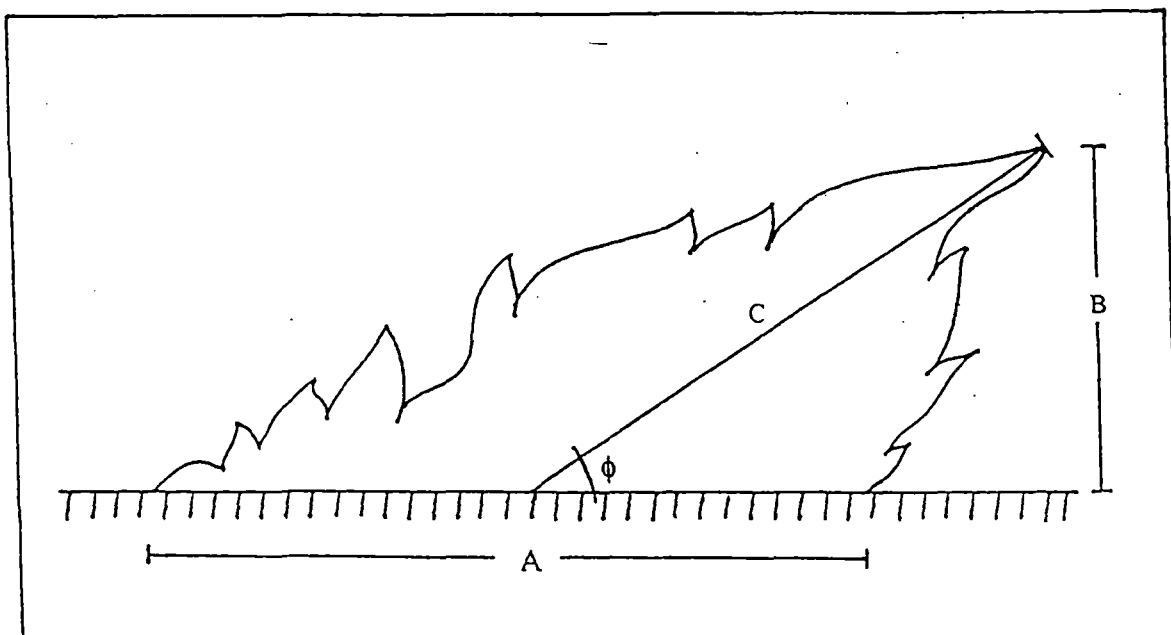
Appendix 4.1. Nutrient concentration (%) of aboveground biomass along a vegetation gradient in Cerrado ecosystem, Reserva Ecologica, IBGE-Brazil. Numbers are mean and standard error. Numbers followed by a different superscription letter denote a significant difference (P<0.05) in concentration when testing between plant communities (Source: Kauffman et al. 1994).

Component	Campo limpo	Campo sujo	Campo cerrado	Cerrado *sensu stricto*
Carbon				
Wood debris < 0.64 cm in diameter	—	—	—	51.47 (0.14)
Wood debris ≥ 0.64 cm in diameter	—	—	—	51.87 (0.16)
Dicot litter	—	50.32 (0.53)^a	52.07 (0.38)^b	52.19 (0.46)^b
Dicots – prefire	—	49.03 (0.32)^a	51.78 (0.28)^b	52.04 (0.33)^b
Dicots – postfire	—	—	51.56 (0.12)	51.75 (0.27)
Live grass	47.89 (0.28)	47.77 (0.08)	47.84 (0.20)^b	47.34 (0.10)^a
Dormant grass	47.36 (0.11)^{ab}	47.10 (0.17)^a	47.71 (0.12)^b	47.06 (0.10)^a
Shrub leaves	—	—	53.19 (0.83)	53.96 (0.37)
Ash	22.50 (0.41)^a	24.81 (1.19)^a	50.88 (1.16)^b	52.62 (1.14)^b
Nitrogen				
Wood debris < 0.64 cm in diameter	—	—	—	0.532 (0.013)
Wood debris ≥ 0.64 cm in diameter	—	—	—	0.362 (0.043)
Dicot litter	—	0.704 (0.028)	0.722 (0.027)	0.752 (0.031)
Dicots – prefire	—	0.792 (0.037)	0.717 (0.083)	0.714 (0.075)
Dicots – postfire	—	—	0.495 (0.024)	0.447 (0.020)
Live grass	0.508 (0.017)^a	0.578 (0.024)^{ab}	0.647 (0.022)^b	0.535 (0.035)^a
Dormant grass	0.261 (0.009)^a	0.282 (0.009)^a	0.313 (0.012)^b	0.317 (0.011)^b
Shrub leaves	—	—	1.274 (0.033)	1.095 (0.080)
Ash	0.233 (0.011)^a	0.264 (0.011)^a	0.873 (0.027)^b	0.953 (0.023)^c
Sulfur				
Wood debris < 0.64 cm in diameter	—	—	—	0.044 (0.004)
Wood debris ≥ 0.64 cm in diameter	—	—	—	0.034 (0.004)
Dicot litter	—	0.073 (0.004)	0.083 (0.007)	0.080 (0.005)
Dicots – prefire	—	0.256 (0.156)	0.086 (0.011)	0.092 (0.004)
Dicots – postfire	—	—	0.069 (0.009)	0.067 (0.005)
Live grass	0.049 (0.003)^a	0.067 (0.003)^b	0.070 (0.066)^b	0.067 (0.003)^b
Dormant grass	0.039 (0.002)	0.034 (0.003)	0.036 (0.003)	0.038 (0.002)
Shrub leaves	—	—	0.135 (0.007)^a	0.109 (0.007)^b
Ash	0.102 (0.002)^a	0.063 (0.011)^b	0.062 (0.002)^b	0.056 (0.004)^b

Appendix 4.2. Nutrient concentration (%) of leaves and stems of Cerrado *sensu lato* trees (N = 5).

	carbon	nitrogen	sulfur
stems	53.62 ±0.58	0.686 ±0.07	0.05 ±0.00
leaves	52.36 ±0.23	1.114 ±0.16	0.07 ±0.00

Appendix.4.3. Bulk density (g cm^{-3}) up to 2.00 m in depth, in soils of Cerrado vegetation gradient, near Brasilia, DF, Brasilia.

Depth	campo limpo	campo sujo	cerrado aberto	cerrado denso
0-10	0.929 ± 0.052	0.958 ± 0.031	0.821 ± 0.035	0.810 ± 0.025
10-20	1.003 ± 0.027	1.097 ± 0.035	0.961 ± 0.019	0.916 ± 0.026
20-30	1.121 ± 0.007	1.120 ± 0.038	0.999 ± 0.016	1.005 ± 0.020
30-50	0.852 ± 0.044	1.103 ± 0.039	0.960 ± 0.015	0.990 ± 0.023
50-100	0.909 ± 0.032	0.985 ± 0.033	0.954 ± 0.007	0.927 ± 0.019
100-200	1.021 ± 0.067	1.086 ± 0.030	0.975 ± 0.027	0.983 ± 0.021

II. Total aboveground biomass, fuel loads, and combustion factors of Brazilian tropical forests and savannas

I. INTRODUCTION

Deforestation and biomass burning of tropical forests are among the most significant anthropogenic activities with respect to the diminution of biological diversity, site productivity, and potential influence on global biogeochemical cycles (Crutzen and Andreae 1990, Wilson 1988). While much of Earth's tropical ecosystems have been dramatically altered, few studies have documented tropical ecosystem biomass or losses by fire. Brazil contains the largest remaining intact tropical forests in the world. These include the unique tropical evergreen forests of Amazonia, the tropical deciduous forests of the Caatinga of northeastern Brazil, and the tropical woodlands and savannas of the Cerrado in central Brazil. All areas are currently undergoing rapid rates of land use change that include deforestation.

Deforestation in the Brazilian Amazon has resulted in the conversion of >230,000 km^2 of tropical forest to pastures, shifting cultivation, or secondary forests (Skole and Tucker 1993). Through agricultural modernization, vast areas of the Brazilian Cerrado have been converted to crops such as soybeans, wheat and corn (Skole et al. 1994). The intact Cerrado communities and areas manipulated for cattle pasture are extremely flammable during the dry season. As much as 50% of the Brazilian Cerrado may burn in a given year (Coutinho 1990). Tropical deciduous forests such as the Caatinga are among the world's most abundant yet, exploited endangered tropical forest ecosystems (Janzen 1988). Salcedo et al. (in press) reported that 200,000 to 500,000 ha of Caatinga vegetation is deforested and burned annually.

In this paper, we present a photographic and data summary of the biomass and levels of consumption following fire (i.e., the combustion factor) of dominant communities or land use scenarios of the Caatinga, Cerrado, and Amazon regions of Brazil. Data presented here are a brief summary of research conducted from 1986 to 1994. Given the importance of the environmental and atmospheric consequences associated with land conversion and biomass burning, it is surprising that such a paucity of data exists on these issues. While data presented in this paper are representative of plant communities or land use scenarios of these three ecoregions, they do not likely cover the range or diversity of fuel loads, composition, structure, or combustion factors likely to be encountered in those extremely diverse ecosystems.

For each of the three aforementioned ecoregions, general information of the dominant vegetation structure, composition and biomass, climate, soils, and predominant land-use practices are given. Each section is composed of a series of either single or paired pre/postfire photographs presented with accompanying quantitative data based on direct biomass measurements. Citations to locate specific references for more detailed analysis are included.

Specifically, this summary includes:

- Photographs of intact-undisturbed plant communities, sites representative of specific land-use activities (e.g. slash or pasture), postfire scenarios, and fire behavior.

- The total aboveground biomass (TAGB) of slashed forests, cattle pastures and natural grasslands. TAGB is partitioned into dominant structural

components including litter, downed and dead wood debris, foliage, grasses, and dicots.

- In standing tropical moist forests surface fuels - litter, dead and downed wood debris, rootmat, dicots are presented. Where available, TAGB is given as well.

- Combustion factors - (the proportion of TAGB or surface fuels consumed by fire).

- Mass of residual uncombusted debris and ash mass following fire.

- Supplemental fire behavior information and photographs representative of typical fires.

How the Photo Series is Presented

Each ecoregional section is composed of specific examples of aboveground biomass that are representative of conditions along predominant vegetation/land-use gradients of the region. In the Caatinga, data from three slashed tropical deciduous forests are presented. They are ordered in progression from the lowest to highest level of biomass consumption. For the Cerrado, we describe biomass along a vegetation gradient from open savanna (Campo limpo) to semi-deciduous woodland (Cerrado sensu stricto-denso). In Amazonia, we present data on biomass at several points along common land use scenarios. These points include intact forests, partially logged forests, slashed primary forests, and second and third-growth forests, and cattle pastures of varying ages.

The TAGB or fuel load of each plant community was partitioned into individual fuel components based on unique plant/fuel characteristics that strongly influence fire behavior and nutrient losses by fire. The fuels data associated with each accompanying photograph are the mean of >30 transects for that site. Total aboveground biomass, fuel loads, and ash mass are reported in Mg ha^{-1} . Dead and downed wood debris volume was quantified utilizing the planar intercept technique (Van Wagner 1968, Brown & Roussopoulous 1974) and were separated into standard time-lag classes based upon diameter (Deeming et al. 1977). Specific variations of the model were created for each plant community in each ecoregion. Mass was calculated from volume data and specific gravity data unique to each site. The mass of grass, litter, attached foliage, and ash mass were determined from quadrats utilizing destructive sampling techniques. Standing

biomass was determined utilizing regression techniques with height, diameter and/or crown area as independent variables and standing biomass as the dependent variable. Following each data table, photographs of individual transects that were representative of the typical biomass/fuel condition are presented. Photos were taken with a 35 mm SLR camera.

Photo 1. Typical slash fire in slashed Caatinga, near Serra Talhada Pernambuco. At the end of the dry season fires like this are common through the tropical dry forests of the world. The dry climate and large concentration of fine fuels results in severe fire behavior and the highest rates of biomass consumption of all slashed tropical forests (photo by J. B. Kauffman).

Photo 2. General overview of slashed Caatinga forest prior to burning, near Serra Talhada Pernambuco, 1989 (photo by J. B. Kauffman).
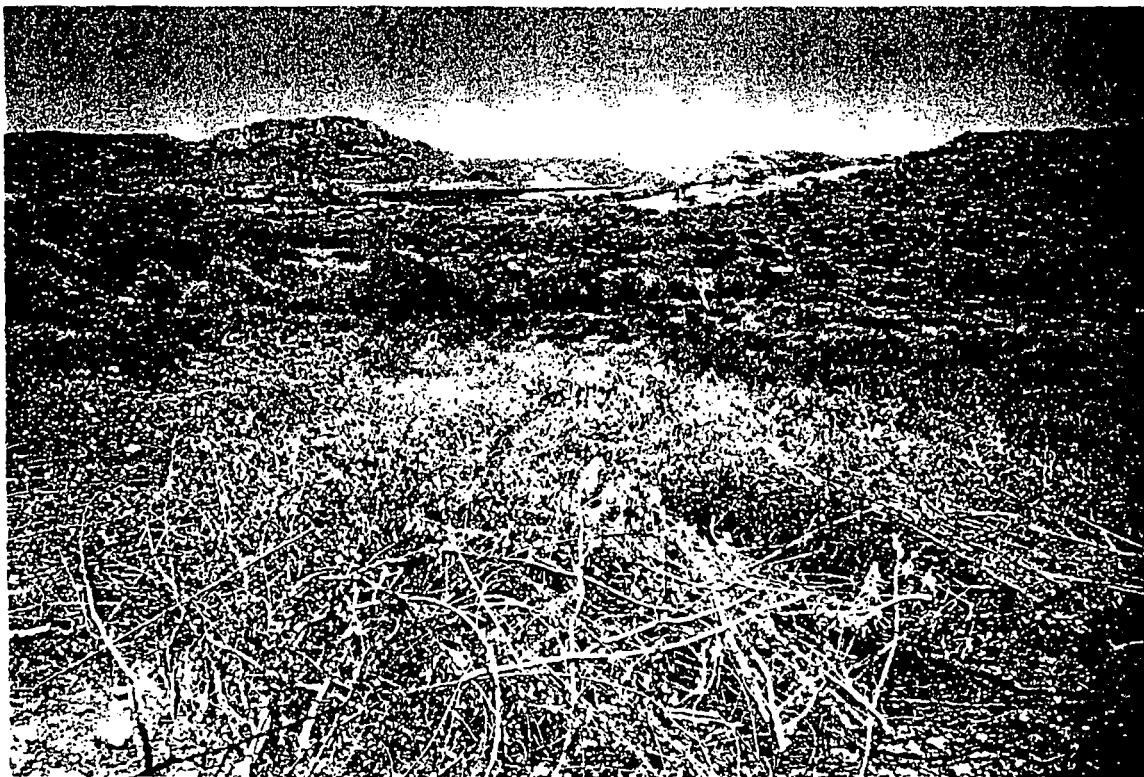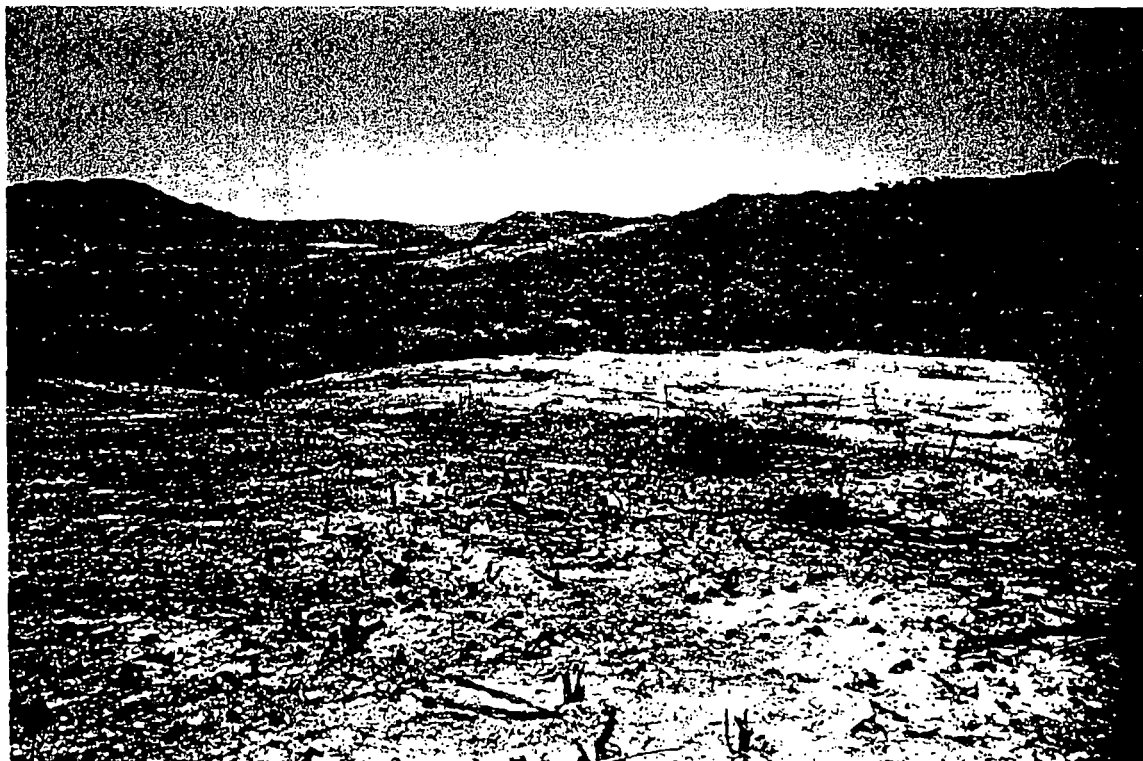

Photo 3. Slashed Caatinga forest following burning, near Serra Talhada Pernambuco, 1989 (photo by J. B. Kauffman).

II. TROPICAL DECIDUOUS FOREST - THE CAATINGA

A. Vegetation Structure and Composition

The semiarid deciduous forests of the Caatinga region comprise the dominant vegetation of northeastern Brazil. These dry forests cover an area 800,000 to 1,000,000 km^2 or approximately 7 to 10% of the land surface of Brazil (Soares 1990, Salcedo et al. 1994). Globally, tropical deciduous forests are the most common of tropical forests, comprising ~42% of all areas occupied by tropical or subtropical forest (Murphy and Lugo 1986). The vegetation consists of xerophytic forests, woodlands, and scrub-woodlands. Members of the Leguminosae and Euphorbiaceae families dominate these ecosystems. In Caatinga forests, stem density is extremely high (~6,000 ha^{-1}); overstory canopy cover generally ranges from 60 to 100% and is 6 to 8 m in height (Eiten 1983, Kauffman et al. 1993, Sampaio et al. 1993). Understory vegetation is sparse and consists primarily of tree seedlings. Lianas are an abundant compound of the forest vegetation. The forest canopy is drought-deciduous; few plants hold leaves during the dry season.

B. Climate and Soils

In the Caatinga region of northeastern Brazil, annual precipitation ranges from 250 to 1000 mm along a west to east gradient. The climate is semi-arid, with a 7 to 10 month dry season occuring from April through November. Drought periods exceeding one year may occur in the interior (Eiten and Goodland 1979). The mean annual temperature is >26°C and relative humidity is typically low.

The topography generally consists of rolling hills with rocky outcrops on hill summits. Soils are derived from limestone and sandstone, and are often quite shallow.

Soil-moisture retention is typically low thus exacerbating the effects of low annual precipitation.

C. Land-use Activities and Fire

Land use centers on shifting cultivation, conversion to livestock pasture, and fuel wood harvest. Shifting cultivation as well as conversion to pasture typically involves cutting and burning the extant vegetation. In general, trees are cut early in the dry season, prior to leaf abscission. Prior to burning, some large wood debris is typically removed for use as fence posts, fuel wood, or charcoal production. Near the end of the dry season the slashed areas are burned, and crops are planted upon commencement of the wet season. Areas are cultivated for 2 to 7 years and then abandoned.

During the slash burning process, Kauffman et al. (1993) reported flame lengths to be 8-10 m in slashed second-growth Caatinga forest near Serra Talhada, Pernambuco. Because of extremely low fuel moisture contents and high concentrations of fine fuels, biomass consumption is among the highest of all slashed tropical forests (75-94%) (Kauffman et al. 1993). Plants in this ecosystem display few adaptations for fire survival; while ~94% of the trees coppiced following cutting, only 10 to 41% survived the slash fires described in this chapter (Sampaio et al. 1993).

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Photo 4. Slashed Caatinga forest prior to an early season burn, Serra Talhada, Pernambuco (Table 1.1). Patterns of land use in this dry forest are similar to most tropical regions of Brazil. The standing forest is cut early in the dry season and allowed to dry for 40-90 days. Towards the end of the dry season, the slashed areas are burned. Upon commencement of the rains, areas are then planted to crops or pasture (photo by D. L. Cummings).

Photo 5. Slashed Caatinga forest following an early season burn, Serra Talhada Pernambuco. This fire was conducted very early in the burning season for this forest type resulting in lower consumption than normal. Note residual unburned slash (photo by D. L. Cummings).

Table 1.1. CAATINGA - SECOND-GROWTH FOREST
Site Location: Serra Talhada, Pernambuco Cite: Kauffman et al. (1993)
Burn Date: September 1989 [75% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	4.0	0.6	95
Attached Foliage	6.1	0.6	85
Wood debris (cm in diam.)			
0 - 0.64	10.2	1.0	85
0.65 - 2.54	26.7	3.7	77
2.55 - 7.62	24.0	9.9	45
> 7.62	2.9	0.8	82
Total wood debris	63.1	15.6	72
Total aboveground	73.7	16.4	78
Ash		3.9	

Photo 6. Slashed Caatinga forest prior to a mid-season burn, Serra Talhada, Pernambuco (Table 1.2) (photo by D. L. Cummings).
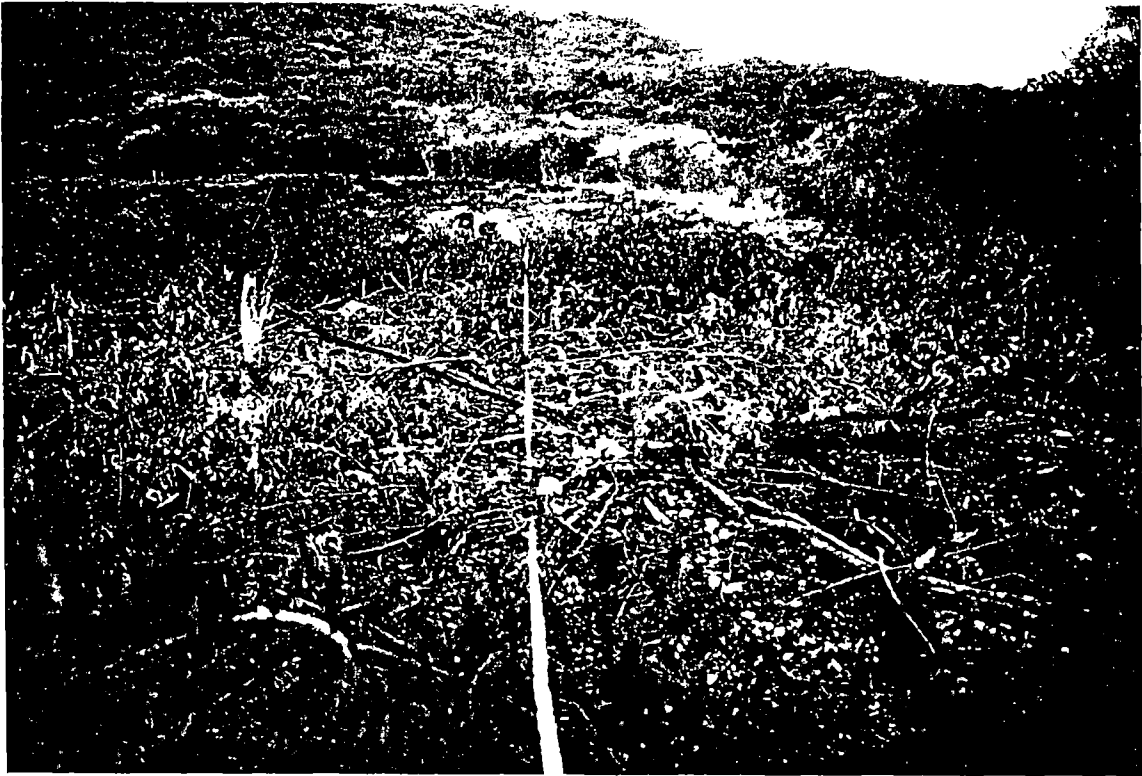
Photo 7. Slashed Caatinga forest following a mid-season burn, Serra Talhada, Pernambuco. Note complete coverage of fire with only larger fuel particles remaining (photo by D. L. Cummings).

Table 1.2. CAATINGA - SECOND-GROWTH FOREST
Site Location: Serra Talhada, Pernambuco Cite: Kauffman et al. (1993)
Burn Date: September 1989 [88% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	3.7	0.0	100
Attached Foliage	7.6	0.0	100
Wood debris (cm in diam.)			
0 - 0.64	12.6	0.0	100
0.65 - 2.54	24.3	0.5	97
2.55 - 7.62	19.0	4.8	74
> 7.62	6.7	3.0	48
Total wood debris	62.6	8.3	87
Total aboveground	74.0	8.3	87
Ash		4.19	

Photo 8. Slashed Caatinga forest prior to a late-season fire, near Serra Talhada, Pernambuco, 1989 (Table 1.3) (photo by D. L. Cummings).

Photo 9. Slashed Caatinga forest following a late season burn, near Serra Talhada, Pernambuco, 1989. Note nearly complete consumption of fuel mass. Compare also differences in ash color with those of photos 5 and 7. In this high consumption fire, the gray color of ash indicates much less organic matter as a result of more complete consumption (photo by D. L. Cummings).

Table 1.3. CAATINGA - SECOND-GROWTH FOREST
Site Location: Serra Talhada, Pernambuco Cite: Kauffman et al. (1993)
Burn Date: October 1989 [95% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR (%)
	Prefire	Postfire	
Litter	3.6	0.0	100
Attached Foliage	6.7	0.0	100
Wood debris (cm in diam.)			
0 - 0.64	11.0	0.0	100
0.65 - 2.54	26.0	0.3	99
2.55 - 7.62	25.3	3.3	83
> 7.62	2.2	0.4	81
Total wood debris	63.5	4.0	93
Total aboveground	73.7	4.0	95
Ash		3.4	

Figure 1. Plant communities of the Cerrado vegetation type of central Brazil. Fires are a common occurrence in savanna and grassland associations (i.e., the gradient from campo limpo to cerrado sensu stricto). Tree heights range from 1 to 5 m for campo sujo, 3 to 6 m for campo cerrado, and 4 to 8 m for cerrado sensu stricto. Density of trees >2 m in height is 600 ha^{-1} in campo cerrado and 833 ha^{-1} in cerrado sensu stricto. Cerradao is a closed-canopy forest.

CAMPO LIMPO   CAMPO SUJO   CAMPO
                               CERRADO   CERRADO
                                           SENSU STRICTO   CERRADÃO
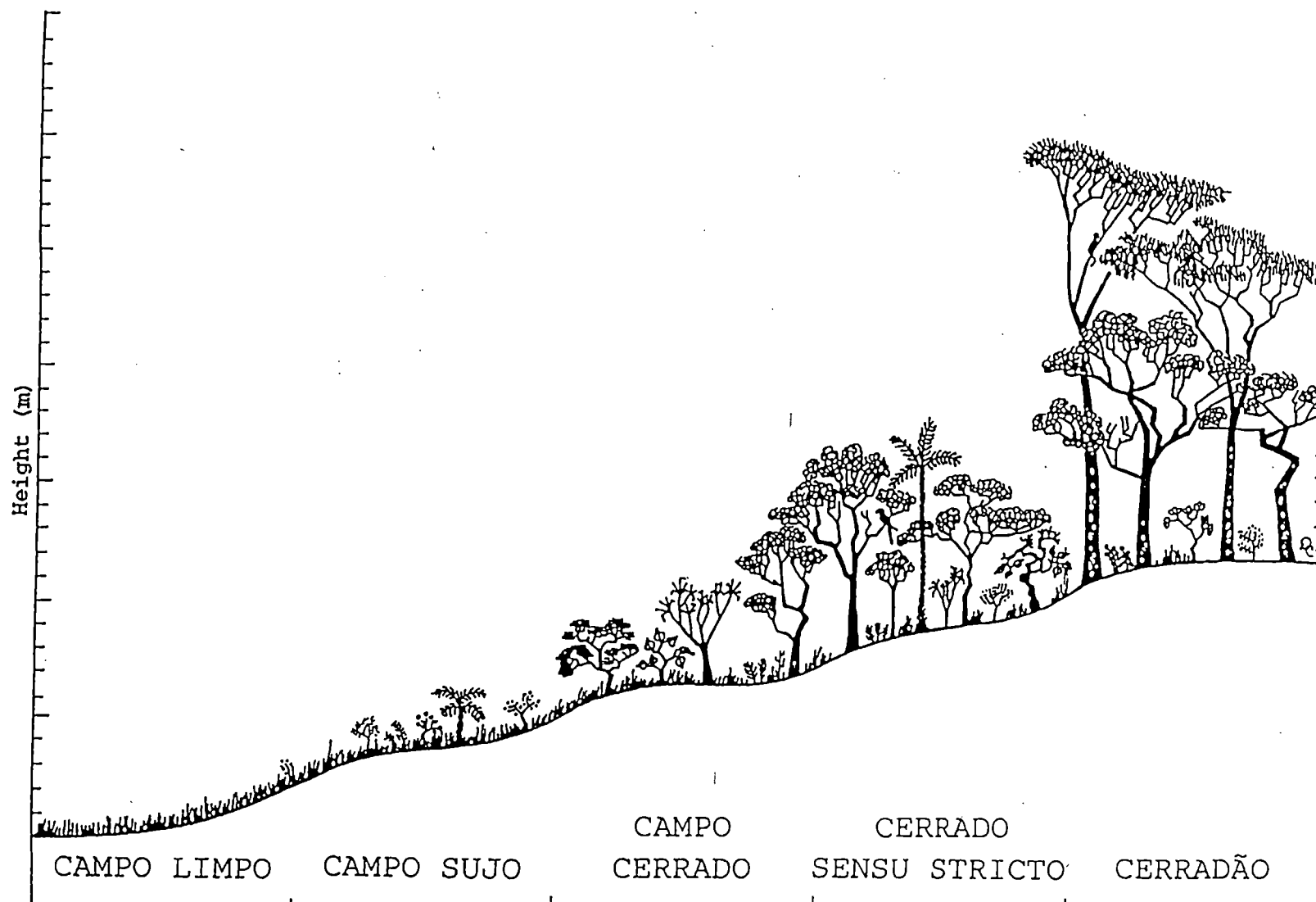
TROPICAL SAVANNAS AND WOODLANDS - CERRADO

A. Vegetation Structure and Composition

The Cerrado is the predominant natural vegetation of central Brazil. This ecoregion occupies an area ranging between 1.5 - 2 million km^2 or ~20% of the total land surface area of the country (Coutinho, 1990). The Brazilian Cerrado is a complex mosaic of pyrophytic plant communities distinguished by a varying structure and composition of tree and grass components. These components are largely influenced by soil fertility and the relative importance of fire; together these two factors create a suite of plant communities along a distinctive vegetation gradient (Goodland 1971, Kauffman et al. 1994). Moving along this gradient from open grassland, to savanna, to closed-canopy semi-evergreen woodland, cerrado may be divided into five "distinct" formations known as (1) campo limpo, (2) campo sujo, (3) campo cerrado, (4) cerrado sensu stricto, and (5) cerradao (Fig. 1). Species diversity and endemism is very high. Furley and Ratter (1988) reported that nearly 800 species of trees and large shrubs occur in the cerrado region, and most are endemic. In the tree-shrub layer alone, Eiten and Sambuichi (1993) reported that 20 to 40 species ha^{-1} commonly occur in this province.

Overstory canopy cover generally ranges from virtually 0% in campo limpo to near 90% in cerradao; average tree height ranges from 3-9 m across the gradient from campo cerrado to cerradão (Goodland 1971). In campo cerrado and cerrado sensu stricto near Brasilia, tree densities (2 m in ht) were 600 stems ha^{-1} and 833 stems ha^{-1}, respectively (Kauffman et al. 1994). Wood debris is typically absent in grasslands but may comprise >15% of the total surface-fuel load in cerrado sensu stricto. In campo

limpo and campo sujo, graminoids (i.e. the Poaceae and Cyperaceae) are dominant floristically and may exceed 90% of the total aboveground biomass (Kauffman et al. 1994). Grass canopies may exceed 1-2 m in height in some areas. In general, increasing tree density along the vegetation gradient generally coincides with decreasing herbaceous biomass and increasing dicot litter biomass (Kauffman et al. 1994).

A distinctive feature of the cerrado compared to other neotropical ecosystems is the low ratio of aboveground to belowground plant biomass. Castro (1995) reported belowground biomass in the campo limpo and campo sujo grasslands to be 16.3 and 30.1 Mg ha^{-1} , respectively. Root biomass in the tree dominated campo cerrado and cerrado sensu stricto was 46.4 and 52.9 Mg ha^{-1} , respectively.

B. Climate and Soils

In the Brazilian Cerrado, annual precipitation generally ranges from 750 to 2000 mm along an east to west gradient, although considerable variation may occur due to topographic influences. The climate is seasonal with a distinct dry season from April through September. Annual temperatures range between 16 and 26°C.

The topography is highly variable over the range of Cerrado ecoregion. Rolling hills and rocky escarpments reaching 1200 m, are present as are vast level plains to near sea level. Soils are generally well drained Oxisols principally derived primarily from shales. They are low in pH (acidic) and have a low cation exchange capacity (CEC). Aluminum concentrations are notably high in many Cerrado soils.

C. Land-use Activities and Fire

In the Cerrado region, land-use history and fire are strongly interconnected. Fire in this ecosystem is an important ecological process having a significant impact on the landscape composition, ecosystem dynamics, and atmospheric chemistry. Virtually all plants possess strong evolutionary adaptations to the frequent occurrence of fire demonstrating a very long period in which fires have been a strong natural influence in this ecosystem. Currently, however, human-caused fires are the predominant agent regulating cerrado distribution and physiognomy (Coutinho 1990). The use of fire in the conversion of grasslands and woodlands to livestock pasture and crop cultivation has greatly accelerated during the previous two decades (Furley and Ratter 1988). Cattle ranchers use fire on an annual or biennial basis to perpetuate existing grassland and to convert scrub or woodland to grassland. Conversely, the widespread replacement of natural cerrado vegetation to soybean production results in the cessation of fire as a natural process in affected lands as well as a decline in C pools of the ecosystem.

The relationship between fire and community structure of the cerrado is circular (Fig. 1). Fires in the campo limpo and campo sujo grasslands are typically of high intensity and exhibit high levels of total biomass consumption (>90%) (Kauffman et al. 1994). Fires in campo cerrado and cerrado sensu stricto burn with lower intensity and rarely burn into tree canopies. This is likely related to a lower biomass of dormant grasses and greater moisture content in surface fuels. These low intensity surface fires would allow for the persistance of arboreal vegetation.

Photo 10. Fire in campo limpo grassland near Brasilia, D.F. Prefire biomass was 7.1 Mg ha^{-1} ; the combustion factor was nearly 100% (photo by J. B. Kauffman).

Photo 11. Fire in cerrado sensu stricto near Brasilia, D.F. Fire behavior and effects are strongly influenced by unique fuel properties in plant communities of the Brazilian cerrado. Fireline intensity, rate of spread, completeness of combustion are typically greater in campo limpo and campo sujo as compared to cerrado sensu stricto. This more severe fire behavior in the campo limpo and campo sujo would facilitate grass dominance by increasing aboveground tissue damage of trees and shrubs (photo by J. B. Kauffman).

Photo 12. Prefire transect in cerrado sensu stricto-denso near Brasilia, D.F. (Table 2.1). Total aboveground biomass of site was 48 Mg ha^{-1} of which 40% (19 Mg ha^{-1}) was considered to be the fuel load. Fuels were defined as all combustible materials <2 m in height with the exception of trunks of trees (photo by J. B. Kauffman).

Photo 13. Postfire transect of cerrado sensu stricto-denso. Note low consumption of thick stems of shrubs and trees. Thick bark to protect meristematic tissues is a typical fire-adaptation of cerrado vegetation (photo by J. B. Kauffman).

Table 2.1. CERRADO - CERRADO SENSU STRICTO *(denso)*
Site Location: Reserva Ecologica do IBGE, Brasilia, DF Cite: Kauffman (unpubl.)
Burn Date: September 1991 [52% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Dicot Litter	6.42	0.04	99
Grass	1.05	0.01	99
Dicot seedlings	2.62	2.54	3
Wood debris (cm in diam.)			
0 - 0.64	0.36	0.03	92
0.65 - 2.54	0.61	0.32	48
2.55 - 7.62	0.82	0.27	67
> 7.62	1.10	0.99	66
Total wood debris	2.89	1.09	66
Arvoretas			
Leaves	0.79	0.05	94
Stems	5.55	5.55	0
Total Arvoretas	6.34	5.60	12
Total mass of shrub/ grass layers–fuels	19.25	9.25	52
Trees (> 2 m in Ht)			
Leaves	10.77	—	—
Wood	18.33	—	—
Total Trees	29.10	—	—
Total aboveground biomass	48.35	38.36	21
Ash		2.56	

Photo 14. Prefire transect in cerrado sensu stricto-aberto near Brasilia, D.F. (Table 2.2). Total aboveground biomass was ~35 Mg ha^{-1} of which 44% (~16 Mg ha^{-1}) was considered to be the fuel load (photo by J. B. Kauffman).

Photo 15. Postfire transect in cerrado sensu stricto-aberto near Brasilia, D.F. While consumption of fine fuels is very high, few plants were killed by fire due to a multitude of evolutionary adaptive traits of fire survival (e.g. thick bark, subterranean buds, anomolous arrangement of meristematic tissues (acaulescent), high crowns, etc. (photo by J. B. Kauffman).

Table 2.2. CERRADO - CERRADO SENSU STRICTO *(aberto)*
Site Location: Reserva Ecologica do IBGE, Brasília, DF   Cite: Kauffman (unpubl.)
Burn Date: September 1991 [74% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha⁻¹)		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Dicot Litter	5.81	0.00	100
Grass	2.13	0.10	95
Dicot seedlings	3.6	0.72	80
Wood debris (cm in diam.)			
0 - 0.64	0.14	0.01	93
0.65 - 2.54	0.27	0.12	56
2.55 - 7.62	0.13	0.09	31
> 7.62	0.25	0.00	100
Total wood debris	0.79	0.22	72
Arvoretas			
Leaves	0.34	0.01	97
Stems	2.91	2.91	0
Total Arvoretas	3.18	2.92	8
Total mass of shrub/ grass layers—fuels	15.51	3.96	74
Trees (> 2 m in Ht)			
Leaves	9.29	—	—
Wood	10.20	—	—
Total Trees	19.49	—	—
Total aboveground biomass	34.99	23.45	33
Ash		3.86	

Photo 16.   Prefire transect in cerrado sensu stricto-aberto near Brasilia, D.F.   This is a transitional stand moving into campo cerrado (Table 2.3) (photo by D. L. Cummings).

Photo 17.   Postfire transect in cerrado sensu stricto-aberto near Brasilia, D.F.   Similar to most cerrado fires, high rates of consumption were measured only for fine fuels (photo by J. B. Kauffman).

Table 2.3. CERRADO SENSU STRICTO - (*aberto*)
Site Location: Reserva Ecologica do IBGE, Brasilia, DF Cite: Kauffman et al. (1994)
Burn Date: September 1990 [84% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})*		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Dicot Litter	3.66	0.00	100
Grass	2.75	0.02	99
Dicot seedlings	1.7	0.45	71
Shrub leaves	0.09	0.04	34
Wood debris (cm in diam.)			
0 - 0.64	0.13	0.09	33
0.65 - 2.54	0.72	0.58	17
> 2.54	0.97	0.42	57
Total wood debris	1.82	1.09	40
Total aboveground	10.03	1.60	84
Ash		2.51	

* Note this includes fuel load only. Tree mass and the stem mass of shrubs 0.5 to 2 m in height were not measured.

Photo 18. Prefire transect in campo cerrado, near Brasilia, D.F. (Table 2.4). This is the mid-point in the transitional vegetation gradient from closed semi-deciduous forest (Cerradao) to pure grassland (campo limpo) in the cerrado ecoregion (photo by D. L. Cummings).

Photo 19. Postfire transect of campo cerrado near Brasilia, D.F. Note uncombusted small snags (left of transect). While mean flame length was ~3 m and the rate of spread was ~15 m min^{-1}, residence time of flaming combustion was 15 sec. Therefore, few standing coarse wood fuel particles (snags) ignite or burn in these fires (photo by D. L. Cummings).

Table 2.4. CERRADO - CAMPO CERRADO
Site Location: Reserva Ecologica do IBGE, Brasilia, DF Cite: Kauffman et al. (1994)
Burn Date: August 1990 [72% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Dicot Litter	1.32	0.00	100
Grass	3.55	0.02	99
Dicot seedlings	2.4	1.22	49
Shrub leaves	0.03	0.00	83
Wood debris (cm in diam.)			
0 - 0.64	0.17	0.07	59
0.65 - 2.54	0.75	0.5	33
> 2.54	0.42	0.42	0
Total wood debris	1.33	0.98	26
Total aboveground	8.62	2.23	72
Ash		1.01	

Photo 20. Prefire transect in Campo sujo near Brasilia, D.F. Grasses comprise the vast majority of aboveground biomass in this ecosystem with a greatly diminished presence of shrubs and hardwood litter (Table 2.5) (photo by J. B. Kauffman).

Photo 21. Postfire transect in campo sujo near Brasilia, D.F. Biomass consumption is extremely high in plant communities given the dominance of fine fuels (photo by J. B. Kauffman).

Table 2.5. CERRADO - CAMPO SUJO
Site Location: Reserva Ecologica do IBGE, Brasilia, DF Cite: Kauffman et al. (1994)
Burn Date: September 1990 [97% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Dicot Litter	0.37	0.00	100
Grass	6.69	0.08	98
Dicot seedlings	0.26	0.08	71
Shrub leaves			-
Wood debris (cm in diam.)			
0 - 0.64	—	—	—
0.65 - 2.54	—	—	—
> 2.54	—	—	—
Total wood debris	—	—	—
Total aboveground	7.32	0.24	97
Ash		0.34	

Photo 22. Prefire transect in campo limpo near Brasilia, D.F. The community is composed of grasses, other graminoids, and fine-stemmed dicots (Table 2.6). While total aboveground biomass is lower than other communities, the biomass of grasses exceeds that of all other communities in the cerrado (photo by J. B. Kauffman).
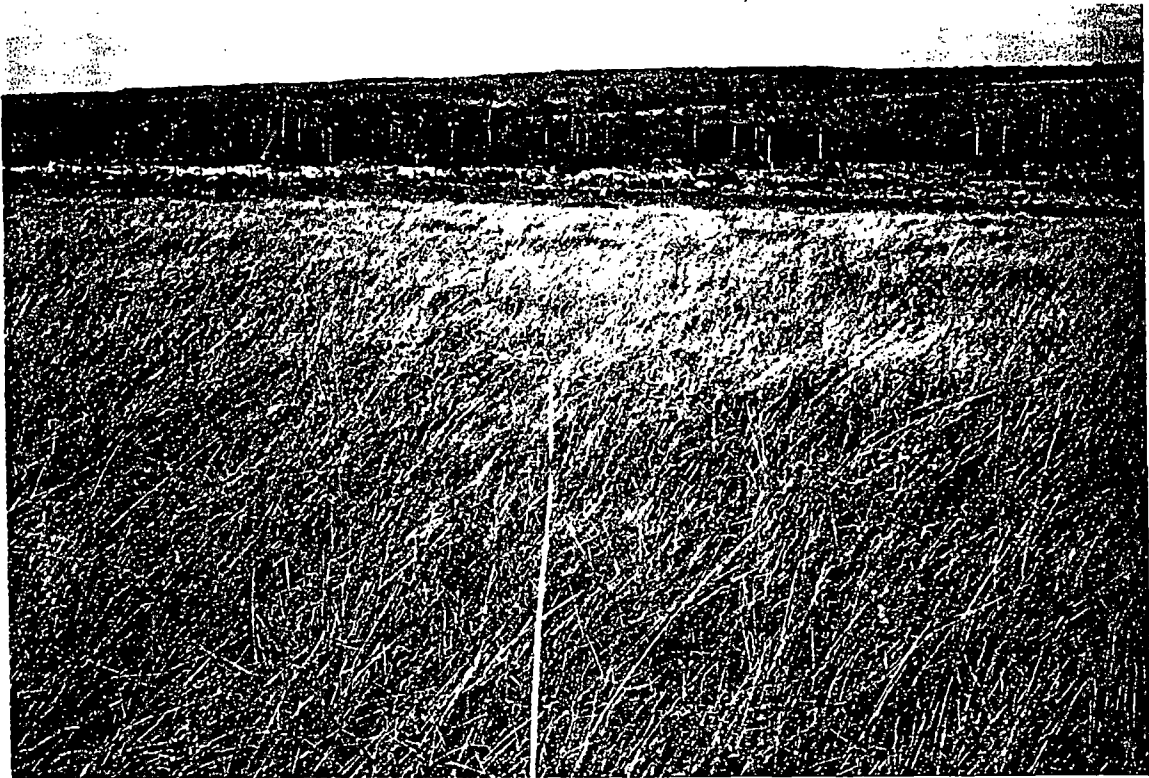

Photo 23. Postfire transect in campo limpo near Brasilia, D.F. As a result of the preponderance of fine fuels, >99% of the total aboveground biomass was consumed by fire (photo by J. B. Kauffman).

Table 2.6. CERRADO - CAMPO LIMPO
Site Location: Reserva Ecologica do IBGE, Brasilia, DF Cite: Kauffman et al. (1994)
Burn Date: September 1990 [100% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Dicot Litter	0.00	0.00	-
Grass	6.71	0.00	100
Dicot seedlings	0.41	0.00	100
Shrub leaves		—	—
Wood debris (cm in diam.)			
0 - 0.64	—	—	—
0.65 - 2.54	—	—	—
> 2.54	—	—	—
Total wood debris	—	—	—
Total aboveground	7.13	0.00	100
Ash		0.78	

Photo 24. Fire in slashed primary tropical moist forest near Maraba, Para, 1991 (Table 3.6) (photo by J. B. Kauffman).
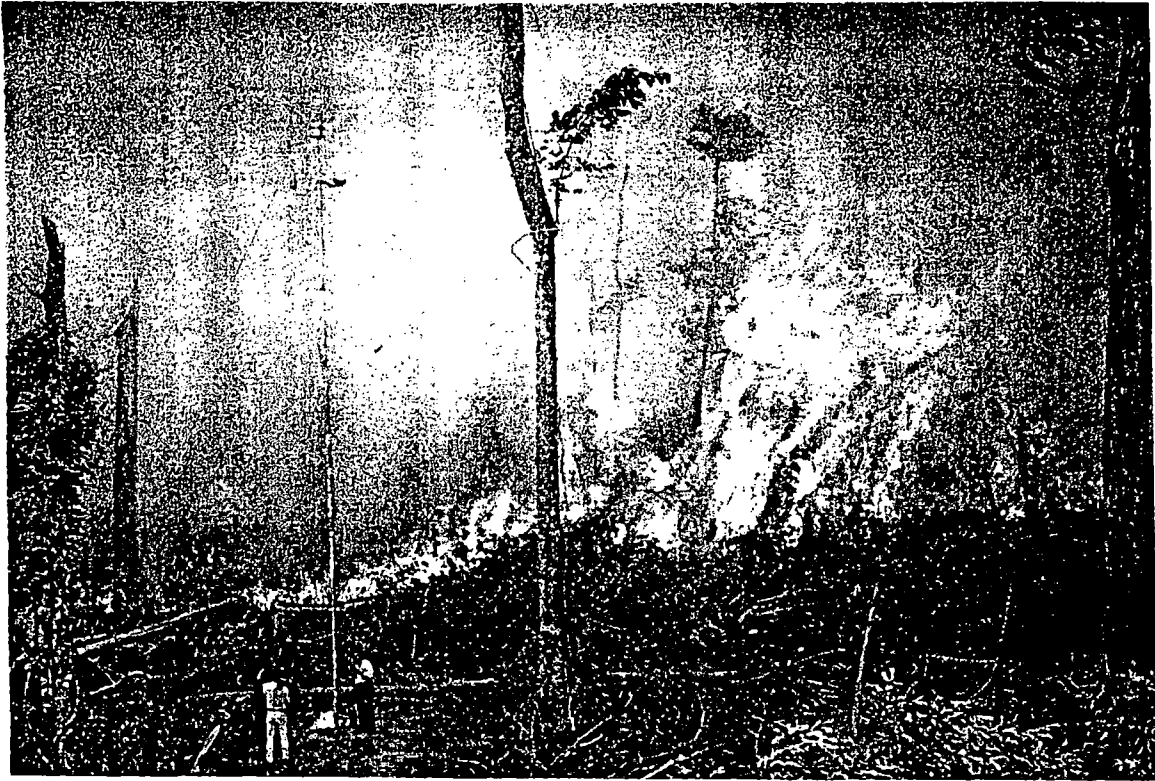

Photo 25. Measurement of fire behabior and flame characteristics in slashed third-growth forest near Maraba, Para, 1991 (photo by J. B. Kauffman).

Photo 26. Early stages of pasture fire near Jamari, Rondonia, 1992 (Table 3.20). Fire behavior in pastures are strongly influenced by weather conditions and the moisture content of grass fuels. In this example, the ratio of live grass to dead was high, resulting in a low to moderate level of fire intensity (photo by J. B. Kauffman).

TROPICAL EVERGREEN FORESTS - AMAZONIA

A. Vegetation Structure and Compsition

The Amazon basin (or the legal Amazon) covers an area of ~5,000,000 km^2 of which ~4,090,000 km^2 is tropical evergreen forest, ~850,000 km^2 is Cerrado, and ~90,000 km^2 is water (Skole and Tucker 1993). Forest composition and structure is highly diverse and dependent on geomorphic position, soil characteristics, and climate. Flood plain forests (Igapo and Varzeas) occur on annually flooded alluvial soils. Upland forests occur on a variety of soil types, most commonly Oxisols and Ultisols. Of the intact forests reported in this chapter, two are the Terra Firme forests and two are in the Amazon Caatinga complex. The latter occur on spodols which are characterized by extremely leached white sands.

In undisturbed primary moist forests, species composition typically includes members of the Leguminosae, Rosaceae, Sapotaceae, Lecythidaceae, and Palmae. Lianas are generally prolific, and both horizontal and vertical canopy structure are quite complex. In Terra Firme (upland) forests, canopy cover is often near 100% except in natural treefall gaps, and canopies range from 25 to 40 m in height. Gentry (1979) noted as many as 91 species >2.54 cm in diameter per 100 m^2 in undisturbed moist forests near Manaus, Amazonas. In contrast, second and third-growth forests which originate following logging are often dominated by species of the Moraceae and Palmae families. Although canopy height growth of 1 m yr^{-1} is not uncommon in these secondary forests, species diversity is limited (Uhl and Jordan 1984; Verissimo et al. 1992). Cattle pastures are dominated by various grasses of African origin along with invasive, dicots, and palms.

Recent estimates of deforestation utilizing remote sensing suggests that from 230,000 km² (through 1988) to 415,000 km² (through 1990) have been deforested in the legal Amazon (Fearnside 1992, Skole and Tucker 1993). This amounts to the deforestation of ~8% of the Amazonian forests. Skole and Tucker (1993) reported that the rate of deforestation averaged ~15,000 km² y¹ and the rate of habitat fragmentation was ~38,000 km y¹ . The contemporary anthropogenic landscapes of the Amazon can be characterized as a mosaic of disturbed standing forests, cattle pastures, areas of shifting cultivation, and second and third-growth forests.

The total aboveground biomass of primary tropical moist forests in Pará and Rondônia ranges from 166 to 430 Mg ha⁻¹ (Kauffman et al. In press; Brown and Lugo 1992; Fearnside 1992). Downed and dead woody debris and forest floor litter are often a minor component of the total aboveground biomass because of high rates of decomposition. However, coarse wood debris can be a significant proportion of the total aboveground biomass in natural treefall gaps and in perturbed secondary forests and pastures.

B. Climate and Soils

In areas of the Brazilian Amazon experiencing high rates of deforestation, annual precipitation is seasonal, ranging from 1750 mm near Paragominas, Para to 2350 mm in Porto Velho, Rondonia (Departamento Nacional de Meterologia, Brasil 1992). In the northern portion of the Amazon Basin (Venezuela), precipitation is as high as 3500 mm y¹ (Heuveldop 1980). In south and western Amazonia where the majority of deforestation occurs, a distinct dry season occurs from June through September, with

precipitation often <50 mm in eastern Para to <100 mm in Rondonia. Average annual temperatures range between 21 and 31°C, with a mean relative humidity of 83%.

The topography in Amazonia is characterized by gently rolling hills dissected by numerous streams and rivers. Soils in Amazonia are diverse; uplands are generally well-drained Oxisols and Ultisols. These soils are acidic, highly weathered, have a low cation exchange capacity, and are high in concentrations of iron and aluminum (Sanchez 1989).

C. Land-use Activities and Fire

The patterns of land use in Amazonia are complex and variable forming a diverse mosaic of lands in shifting cultivation, fallow lands, cattle pastures, primary forests, and logged forests. Following logging or agricultural activities, secondary forests may quickly establish and revert to tall canopy forest. More commonly, however, secondary forests are cut 4 to 20 years after abondonment and utilized for shifting cultivation or converted to cattle pastures.

Deforestation and burning associated with forest conversion to cattle pasture and agricultural practices has greatly increased the prevalence of fire in Amazonia. However, a distinctive feature of intact primary forests is their apparent immunity to fire (Kauffman et al. 1988, Uhl and Kauffman 1989). This is due to unique microclimatic conditions including high relative humidities and high fuel moisture contents. For example, litter moisture content in a slashed primary forest at the time in which it was burned was 7%. In contrast, litter moisture content was 36% in an adjacent uncut primary forest (Kauffman et al. in press). Forest fragmentation due to logging or clearing practices have substantially increased fire probability near forest edges through

an increase in temperatures and a decrease in relative humidity. This, coupled with an abundant ignition source associated with the widespread use of fire in pasture management and agricultural burnings has resulted in a dramatic increase in the frequency and areal extent of fires in the Amazon (Uhl and Kauffman 1990).

Fires in logged forests or those intentionally cut for agricultural purposes are significant sources of emissions influencing atmospheric biogeochemistry as well as site productivity. The losses of nutrients associated with slash fires in the Amazon are extremely high and far exceed natural rates of recovery (Kauffman et al. in press). While the percentage of available fuel consumed in slashed and burned primary forests is generally low (39-56%), the actual mass consumed may be >150 Mg ha^{-1} (Kauffman et al. In press). The process of site degradation and atmospheric emissions of pollutants continues when secondary forests are slash-and- burned; from 43 to 88% of the aboveground fuel load are consumed by fires in these areas.

Vegetation of the primary tropical evergreen forests are poorly adapted for persistence following the introduction of anthropogenic fires. In standing forests ecotonal to openings, escaped fires of very low intensity killed 36 to 54% of the standing trees (Kauffman 1991). In slashed forests, fires killed 65 to 69% of the residual standing trees. Competition by pasture grasses and frequent fires further depleted the natural diversity of these forests.

Photo 27. Intact primary tropical moist forest-Terra Firme, near Paragonimas, Para (Table 3.1). Litter and wood debris comprised ~15% of the total aboveground biomass. Microclimate in intact forests are such that natural fires are virtually impossible under current weather-patterns (photo by J. B. Kauffman).

Table 3.1. AMAZONIA - INTACT PRIMARY TROPICAL MOIST FOREST*
Site Location: Paragominas, Para Cite: Uhl and Kauffman (1990)
June 1987

Component	FUEL LOADING (Mg ha^{-1})
Litter	4.1
Wood debris (cm in diam.)	
0 - 0.64	0.9
0.65 - 2.54	2.6
2.55 - 7.62	5.7
> 7.62 sound	29.2
> 7.62 rotten	13.1
Total wood debris	51.5
Total litter and wood debris	55.6

* Total aboveground biomass of this forest is estimated to be 333 to 362 Mg ha^{-1} (Uhl et al. 1988).

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Photo 28. Intact primary tropical rainforest-Tierra Firme, near San Carlos de Rio
Negro, Venezuela (Table 3.2). These are the dominant upland forest types of rainforest
ecosystems of the northern Amazon. The forest canopy is 20-30 m in height. A
prominent rootmat is present in these forests (photo by J. B. Kauffman).

Table 3.2. AMAZONIA - INTACT PRIMARY TROPICAL RAINFOREST - TIERRA FIRME*
Site Location: San Carlos de Rio Negro, Venezuela Cite: Kauffman et al. (1988)
January 1986

Component	FUEL LOADING (Mg ha^{-1})
Litter	2.4
Rootmat	48.6
Wood debris (cm in diam.)	
0 - 0.64	0.61
0.65 - 2.54	1.7
2.55 - 7.62	3.1
> 7.62 sound	3.0
> 7.62 rotten	4.6
Total wood debris	12.9
Total litter and wood debris	64.0

* These are the dominante upland tropical rainforest over Oxisols of the northwestern Amazon Basin. Total aboveground biomass was 399 Mg ha^{-1} . Standing tree biomass was 335 Mg ha^{-1} (Jordan and Uhl 1978).

Photo 29. Intact primary tropical rainforest-Amazon Caatinga, near San Carlos de Rio Negro, Venezuela (Table 3.3). Soils are Spodosols characterized by bleached fine sand in surface horizons. Forest canopy is closed and ~20-30 m in height (photo by J. B. Kauffman).

Photo 30. Intact primary tropical rainforest-Bana, near San Carlos de Rio Negro, Venezuela (Table 3.4). Soils are Spodosols with_coarse sands in surface horizons. The forest canopy is open and 5-10 m tall (photo by J. B. Kauffman).

Table 3.3. AMAZONIA - INTACT PRIMARY TROPICAL RAINFOREST - CAATINGA*
Site Location: San Carlos de Rio Negro, Venezuela Cite: Kauffman et al. (1988)
January 1986)

Component	FUEL LOADING (Mg ha⁻¹)
Litter	3.2
Rootmat	35.8
Wood debris (cm in diam.)	
0 - 0.64	0.3
0.65 - 2.54	1.0
2.55 - 7.62	1.6
> 7.62 sound	0.2
> 7.62 rotten	2.3
Total wood debris	5.3
Total litter and wood debris	44.0

* Amazon Caatinga should not be confused with the forest ecosystem of the Caatinga region of northeastern Brazil. This area is a tropical evergreen forest over Spodosols in contrast to the tropical deciduous forests of northeastern Brazil. Total aboveground biomass of this forest type was 229 Mg ha⁻¹ . Standing mass of trees was 185 Mg ha⁻¹ (Herrera 1979).

Table 3.4. AMAZONIA - INTACT PRIMARY TROPICAL RAINFOREST - BANA*
Site Location: San Carlos de Rio Negro, Venezuela Cite: Kauffman et al. (1988)
January 1986

Component	FUEL LOADING (Mg ha^{-1})
Litter	2.8
Rootmat	8.2
Wood debris (cm in diam.)	
0 - 0.64	0.2
0.65 - 2.54	0.9
2.55 - 7.62	0.5
> 7.62 sound	0.0
> 7.62 rotten	0.0
Total wood debris	1.6
Total litter and wood debris	13.0

* A low statured tropical evergreen forest over Spodosols (white sands) with a total aboveground biomass of 50 Mg ha^{-1} . Standing biomass of trees is 37 Mg ha^{-1} (Herrera 1979).

Photo 31. Partially logged forest near Paragonimas, Para (Table 3.5). Currently, this is a very extensive form of land use in the Amazon Basin. Typically, these sites are converted to agriculture or cattle pasture after logging. Whereas, fire is a virtual impossibility in intact forests, sustained combustion is possible in these exploited forests following six rainless days (Uhl and Kauffman 1990). Accidental fires are common in logged forests (photo by J. B. Kauffman).

Table 3.5. AMAZONIA - PARTIALLY LOGGED PRIMARY MOIST FOREST*
Site Location: Paragominas, Para Cite: Uhl and Kauffman (1990)
June 1987

Component	FUEL LOADING (Mg ha^{-1})
Litter	6.1
Wood debris (cm in diam.)	
0 - 0.64	3.3
0.65 - 2.54	8.7
2.55 - 7.62	23.4
> 7.62 sound	120.2
> 7.62 rotten	17.2
Total wood debris	172.7
Total litter and wood debris	178.8

* Approximately 50% of the canopy was destroyed in an operation which resulted in the removal of approximately 1 to 2% of all stems >10 cm dbh (Uhl and Vieira 1989).

Photo 32. Slashed primary tropical moist forest near Maraba, Para (Table 3.6). This site had the greatest TAGB of all sampled sites largely due to large quantities of coarse wood debris > 20.5 cm diameter (photo by D. L. Cummings).

Photo 33. Postfire primary slashed forest. The majority of fine fuels were consumed leaving only coarse wood as residual uncombusted debris (photo by D. L. Cummings).
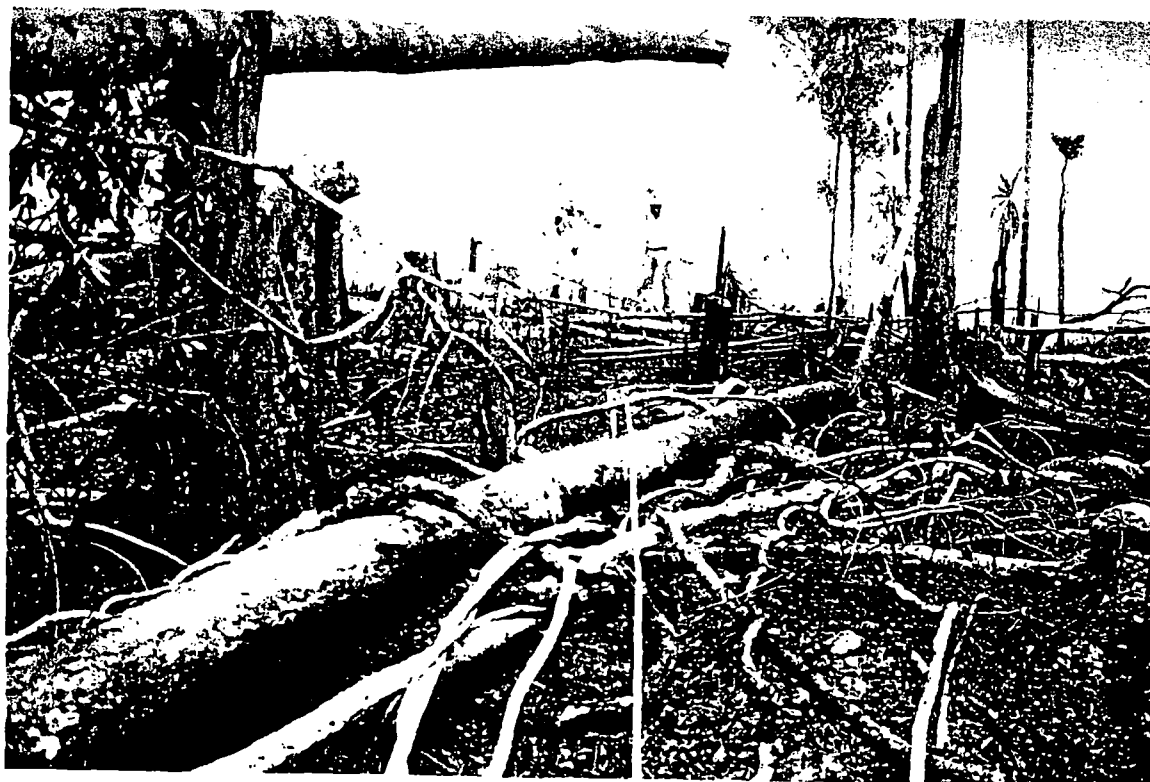
Table 3.6. AMAZONIA - SLASHED PRIMARY TROPICAL MOIST FOREST
Site Location: Maraba, Para Cite: Kauffman et al. (1995)
Burn Date: September 1991 [48% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha^{-1}) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	16.2	0.1	100
Rootmat	0.0	0.0	-
Total forest floor	16.2	0.1	100
Dicot seedlings	0.4	0.0	100
Attached foliage	4.9	0.0	100
Wood debris (cm in diam.)			
0 - 0.64	3.0	0.1	96
0.65 - 2.54	17.2	1.9	89
2.54 - 7.62	33.0	11.3	65
7.63 -20.5 sound	53.0	39.6	25
rotten	3.6	0.0	100
Total	56.6	39.6	30
> 20.5 sound	283.7	154.1	46
rotten	19.5	0.0	100
Total	303.3	154.1	49
Total wood debris	413.1	207.0	45
Total aboveground fuel	434.6	207.1	48
Ash		10.9	

Photo 34. Slashed primary tropical moist forest prior to burning. Jamari, Rondonia (Table 3.7). As few trees were remaining standing, fuel loads are a good indicator of TAGB (photo by J. B. Kauffman).

Photo 35. Slashed primary tropical moist forest following burning, Jamari, Rondonia. The combustion factor was highest for this site than for any other sampled primary forest. This site was to be planted directly to pasture following fire (photo by J. B. Kauffman).

Table 3.7. AMAZONIA - SLASHED PRIMARY TROPICAL MOIST FOREST
Site Location: Jamari, Rondonia Cite: Kauffman et al. (1995)
Burn Date: September 1992 [57% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR (%)
	Prefire	Postfire	
Litter	11.8	0.1	99
Rootmat	3.0	0.0	100
Total forest floor	14.8	0.1	99
Dicot seedlings	0.8	0.0	100
Attached foliage	9.0	0.1	100
Wood debris (cm in diam.)			
0 - 0.64	7.6	0.1	98
0.65 - 2.54	20.1	1.0	89
2.54 - 7.62	54.6	7.5	79
7.63 -20.5 sound	93.4	45.3	41
rotten	3.8	0.9	72
Total	97.2	46.2	52
> 20.5 sound	144.7	91.5	34
rotten	13.2	9.1	44
Total	157.8	100.6	36
Total wood debris	337.4	155.4	54
Total aboveground fuel	361.2	155.6	57
Ash		7.2	

Photo 36. Slashed primary tropical moist forest prior to burning, Jacunda, Para (Table 3.8). Note depth of slash is ~2 m (photo by Brent Holben).
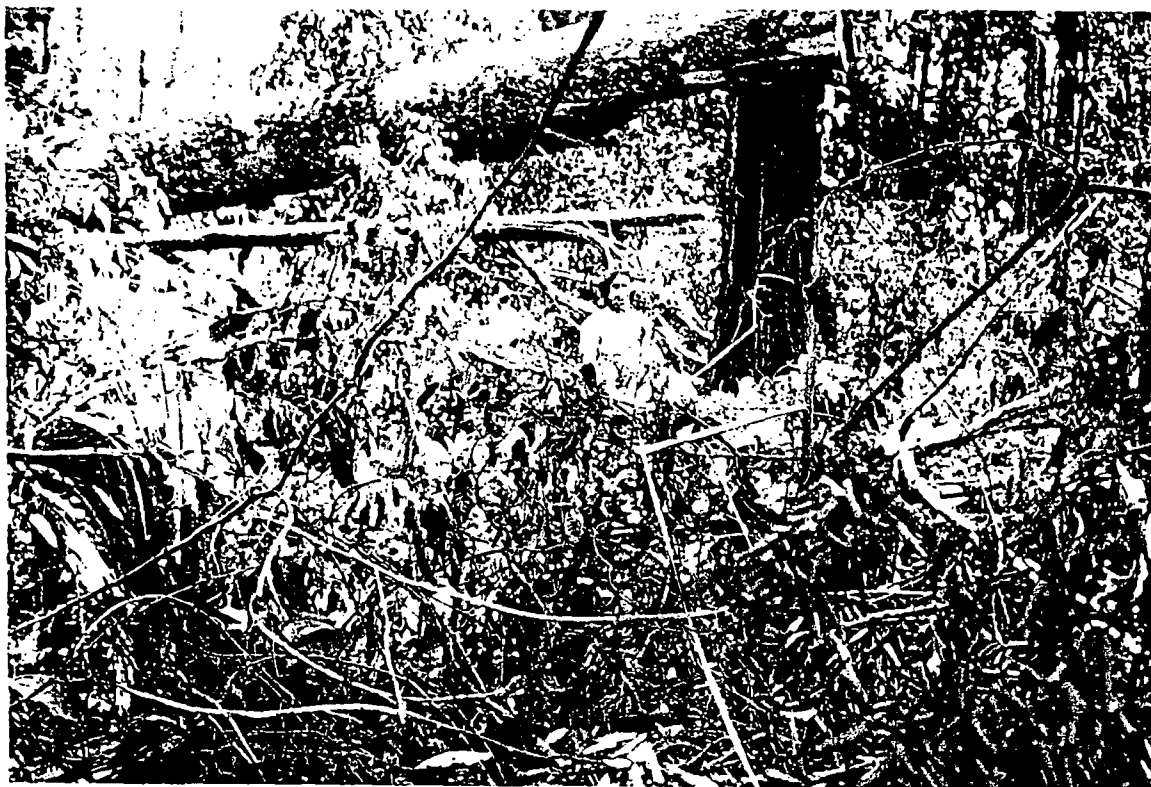

Photo 37. Slashed primary tropical moist forest following burning, Jacunda, Para. Note complete combustion of the large log above the author. This site was to be planted to crops for 2 years prior to conversion to cattle pasture (photo by D. L. Cummings).

Table 3.8. AMAZONIA - SLASHED PRIMARY TROPICAL MOIST FOREST
Site Location: Jacunda, Para   Cite: Kauffman et al. (1995)
Burn Date: September 1990 [53% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha^{-1}) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	11.8	0.0	100
Rootmat	0.0	0.0	—
Total forest floor	11.8	0.0	100
Dicot seedlings	1.1	0.0	100
Attached foliage	2.8	0.3	78
Wood debris (cm in diam.)			
0 - 0.64	3.5	0.3	78
0.65 - 2.54	18.8	3.6	77
2.54 - 7.62	31.6	12.9	55
Total	67.8	49.3	25
Total	155.0	73.5	44
Total wood debris	276.6	139.6	49
Total aboveground fuel	292.4	139.9	53
Ash		8.8	

Photo 38. Slashed primary tropical moist forest prior to burning, Santa Barbara, Rondonia (Table 3.9). A significant rainfall event the night of the fire likely depressed consumption (photo by J. B. Kauffman).

Photo 39. Slashed primary tropical moist forest following burning, Santa Barbara, Rondonia. This site was to be planted to rice and manihot (photo by D. L. Cummings).

Table 3.9. AMAZONIA - SLASHED PRIMARY TROPICAL MOIST FOREST
Site Location: Jacunda, Para Cite: Kauffman et al. (1995)
Burn Date: September 1992 [42% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	11.0	0.2	99
Rootmat	12.7	3.3	74
Total forest floor	23.4	3.4	85
Dicot seedlings	0.8	0.1	67
Attached foliage	6.4	0.1	95
Wood debris (cm in diam.)			
0 - 0.64	5.4	0.1	95
0.65 - 2.54	15.7	1.2	90
2.54 - 7.62	35.9	11.2	54
7.63-20.5 sound	65.5	45.5	16
rotten	4.5	0.9	91
Total	70.0	46.0	34
>20.5 sound	134.5	102.9	22
rotten	8.1	0.0	100
Total	132.7	102.9	22
Total wood debris	259.9	161.3	35
Total aboveground fuel	290.2	165.1	42
Ash		9.4	

Photo 40. Slashed primary tropical moist forest prior to burning, Jamari, Rondonia. An abundance of trees in this site were not cut prior to burning resulting in a lower quantity of slash fuels (Table 3.10) (photo by D. L. Cummings).

Photo 41. Slashed primary tropical moist forest following burning, Jamari, Rondonia. A short drying period between cutting and burning, large numbers of residual standing trees, and rain the night of the fire likely reduced biomass consumption at this site. This area was to be planted to rice and then converted to livestock pasture (photo by D. L. Cummings).

Table 3.10. AMAZONIA - SLASHED PRIMARY TROPICAL MOIST FOREST*
Site Location: Jamari, Rondonia Cite: Hughes (In prep.)
Burn Date: September 1993 [38% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	14.6	0.1	99
Rootmat	0.0	0.0	--
Dicot seedlings	0.6	0.0	100
Attached foliage	6.4	0.1	99
Wood debris (cm in diam.)			
0 - 0.64	5.4	0.1	98
0.65 - 2.54	17.0	1.0	94
2.54 - 7.62	32.2	8.8	73
7.63-20.5 sound	54.0	44.7	17
rotten	4.3	0.7	83
>20.5 sound	173.5	139.1	20
rotten	3.4	0.0	100
Total wood debris	289.8	194.4	33
Total aboveground	311.3	194.5	38
Ash		7.8	

* Primary forest cut and burned for conversion to pasture.

Photo 42. Slashed second-growth forest (Capoeira secondaria) prior to burning, Jamari, Rondonia (Table 3.11). The primary forest on this site had been cut and burned 6 years previously. The majority of TAGB in this system was residual wood debris from the primary forest (photo by D. L. Cummings).

Photo 43. Slashed second-growth forest (Capoeira secondaria) following burning, Jamari, Rondonia. Accumulated wood from second-growth forest was consumed in greater amounts than residual wood originating from primary forest (photo by D. L. Cummings).

Table 3.11. AMAZONIA - SLASHED SECOND-GROWTH FOREST
Site Location: Jamari, Rondonia Cite: Kauffman and Cummings (1995b)
Burn Date: September 1992 [57% Total Fuel Consumption]

| Component | FUEL LOADING ($Mg\,ha^{-1}$) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	11.1	2.6	80
Rootmat	3.0	0.4	99
Dicot seedlings	0.2	0.0	100
Attached foliage	2.2	0.1	90
Wood debris (cm in diam.)			
0 - 0.64	3.9	0.2	90
0.65 - 2.54	13.9	2.3	85
2.54 - 7.62	18.3	4.4	75
7.63 -20.5 sound *accumulated	11.1	6.8	39
sound residual	32.5	16.5	54
rotten residual	9.3	3.3	49
> 20.5 sound	68.1	46.7	40
rotten	4.0	1.2	70
palms	0.0	0.0	-
Total wood debris	161.2	80.9	54
Total aboveground fuel	177	83.6	57
Ash		6.6	

* New wood is wood that originates from the second-growth forest. Residual wood and all wood >20.5 cm diameter was wood that originated from the primary forest.

Photo 44. Slashed second-growth forest (Capoeira secondaria) prior to burning, Jacunda, Para (Table 3.12) (photo by D L. Cummings).

Photo 45. Slashed second-growth forest (Capoeira secondaria) following burning, Jacunda, Para. The combustion factor was likely depressed by a significant precipitation event that occurred ~2 hours following ignition. Nevertheless, the landowner considered consumption on the site to be adequate for pasture establishment (photo by D. L. Cummings).

Table 3.12. AMAZONIA - SLASHED SECOND-GROWTH FOREST
Site Location: Jacunda, Para   Cite: Kauffman and Cummings (1995b)
Burn Date: September 1990 [43% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	11.0	0.1	99
Rootmat	0.0	0.0	—
Dicot seedlings	0.2	0.0	100
Attached foliage	1.2	0.1	89
Wood debris (cm in diam.)			
0 - 0.64	2.3	0.2	89
0.65 - 2.54	13.6	3.3	67
2.55 - 7.62	13.6	10.2	27
7.63 -20.5	52	37.1	28
> 20.5 sound	27.6	18.9	14
Total wood debris	109.1	69.7	37
Total aboveground fuel	121.4	70.7	43
Ash		—	

Photo 46. Slashed second-growth forest (Capoeira secondaria) prior to burning, Santa Barbara, Rondonia (Table 3.13) (photo by D. L. Cummings).

Photo 47. Slashed second-growth forest (Capoeira secondaria) following burning, Santa Barbara, Rondonia. This site had the highest combustion factor of all second-growth forests. Following the fire, the landowner piled and burned residual uncombusted wood debris to further decrease residual biomass on site. This is a common land use practice among agriculturalists of this region (photo by D. L. Cummings).

Table 3.13. AMAZONIA - SLASHED SECOND-GROWTH FOREST*
Site Location: Santa Barbara, Rondonia   Cite: Hughes (In prep.)
Burn Date: September 1993 [63% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	13.3	0.1	99
Rootmat	0.0	0.0	—
Dicot seedlings	0.1	0.1	0.0
Attached foliage	1.7	0.1	97
Wood debris (cm in diam.)			
0 - 0.64	3.0	0.1	97
0.65 - 2.54	11.2	1.7	85
2.55 - 7.62	12.7	3.1	76
7.63 -20.5 sound *accumulated	11.6	5.9	49
sound residual	5.7	4.4	23
rotten residual	6.6	1.4	78
> 20.5 sound	23.1	13.9	40
rotten	14.6	8.0	45
Total wood debris	88.6	38.6	57
Total aboveground fuel	103.7	38.9	63
Ash		3.1	

* This site had been converted from primary forest to shifting cultivation 6 years prior to sampling. Site experienced one cultivation/fallow cycle. This cycle included cultivation for 2 years and fallowed to second-growth forest for 4 years. This second-growth forest was cut and burned to initiate a second cycle of shifting cultivation; crops will include corn, rice, and manihot.

Photo 48. Slashed third-growth forest (Capoeira terciaria) prior to burning, Jamari, Rondonia (Table 3.14). TAGB of third-growth forests are only 15 to 30% of that of primary forest. In addition, the rate of biomass accumulation of third-growth forest is lower than second-growth forests. Residual fuels from the primary forest comprise the majority of TAGB at these sites (photo by J. B. Kauffman).

Photo 49. Slashed third-growth forest (Capoeira terciaria) following burning, Jamari Rondonia. Note large residual coarse wood debris. Fine fuels from regenerating forest are typically consumed in large quantities (photo by J. B. Kauffman).

Table 3.14. AMAZONIA - SLASHED THIRD-GROWTH FOREST
Site Location: Jamari, Rondonia Cite: Kauffman and Cummings (1995b)
Burn Date: September 1992 [60% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Litter	13.7	0.1	99
Rootmat	2.3	0.6	74
Dicot seedlings	0.2	0.1	50
Attached foliage	2.2	0.0	100
Wood debris (cm in diam.)			
0 - 0.64	3.9	0.0	100
0.65 - 2.54	10.6	0.7	93
2.55 - 7.62	14.1	6.0	57
7.63 -20.5 sound accumulated	5.9	4.3	27
sound residual	6.7	5.2	32
rotten	0.6	0.3	61
> 20.5 sound	57.4	46.1	27
rotten	1.0	0.0	100
palms	1.5	0.0	100
Total wood debris	101.9	62.6	53
Total aboveground fuel	120.3	63.4	60
Ash		4.2	

Photo 50. Slashed third-growth forest (Capoeira terciaria) prior to burning, Maraba, Para (Table 3.15). This site had undergone two rotations of shifting cultivation prior to this cycle. Residual debris from the primary forest were lower here than other sampled third-growth forests (photo by D. L. Cummings).

Photo 51. Slashed third-growth forest (Capoeira terciaria) following burning, Maraba, Para. The dominance of fine wood debris coupled with an exceptional dry season (1991) in Para resulted in very high rates of biomass consumption at this site (i.e. the combustion factor was 88%) (photo by D. L. Cummings).

Table 3.15. AMAZONIA - SLASHED THIRD-GROWTH FOREST
Site Location: Maraba, Para Cite: Kauffman and Cummings (1995b)
Burn Date: September 1991 [88% Total Fuel Consumption]

. Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Litter	14.1	0.0	100
Rootmat	0.0	0.0	—
Dicot seedlings	—	—	—
Attached foliage	4.5	0.0	99
Wood debris (cm in diam.)			
0 - 0.64	4.2	0.0	99
0.65 - 2.54	14.1	0.9	92
2.54 - 7.62	9.8	2.0	82
7.63 -20.5 sound	8.2	2.6	66
rotten	0.5	0.0	100
> 20.5 sound	3.5	0.8	78
rotten	4.9	1.6	67
Total wood debris	45.2	7.9	84
Total aboveground fuel	63.8	7.9	88
Ash		3.7	

Photo 52. Slashed third-growth forest (Capoeira terciaria) prior to burning, Jamari, Rondonia (Table 3.16). A postfire photo of the site was unavailable (photo by R. F. Hughes).

Table 3.16. AMAZONIA - SLASHED THIRD-GROWTH FOREST*
Site Location: Jamari, Rondonia Cite: Hughes (In prep.)
Burn Date: September 1993 [64% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha⁻¹) Prefire	Postfire	COMBUSTION FACTOR (%)
Litter	10.6	0.1	100
Rootmat	1.8	0.8	57
Dicot seedlings	1.9	0.0	100
Attached foliage	2.5	0.0	100
Wood debris (cm in diam.)			
0 - 0.64	4.5	0.1	99
0.65 - 2.54	11.6	0.8	93
2.55 - 7.62	12.7	4.3	66
7.63 -20.5 sound accumulated	5.7	5.5	3
sound residual	3.6	3.5	5
rotten	3.2	1.5	52
> 20.5 sound	11.6	9.6	17
rotten	1.0	0.0	100
Total wood debris	53.9	25.3	53
Total aboveground fuel	70.2	25.4	64
Ash		4.0	

* This site was converted from primary forest to shifting cultivation 12 years prior to sampling. Site experienced 2 cultivation/fallow cycles, each consisting of 2 years of cultivation followed by 4 years of fallow as second or third-growth forest. Third-growth forest was cut and burned to initiate a third cycle of cultivation; crops include corn, manihot, and sugar cane.

Photo 53. Livestock pasture prior to burning. Jamari, Rondonia (Table 3.17). Mean fuel depth of fine fuels (grasses and dicots) varies from 1.5 to 2 m in recently formed pastures such as this one. Recently formed pastures are typified by an abundance of residual coarse-wood debris, sprouting dicots, and vigorous grass growth (photo by D. L. Cummings)

Photo 54. Livestock pasture following burning, Jamari, Rondonia. Fine fuels were consumed in high quantities while consumption of large woody debris was moderate (photo by D. L. Cummings).

Table 3.17. AMAZONIA - LIVESTOCK PASTURE - 4TH YEAR SINCE PRIMARY
DEFORESTATION
Site Location: Jamari, Rondonia Cite: Kauffman and Cummings (1995a)
Burn Date: September 1992 [40% Total Fuel Consumption]

Component	FUEL LOADING (Mg ha^{-1})		COMBUSTION FACTOR
	Prefire	Postfire	(%)
Litter*	11.6	1.3	96
Live grass	3.8	1.1	85
Dicot seedlings	0.3	0.3	0
Wood debris (cm in diam.)			
0 - 0.64	0.1	0.0	99
0.65 - 2.54	0.3	0.2	86
2.55 - 7.62	4.2	4.0	39
7.63 -20.5 sound	32.9	27.1	13
rotten	4.5	2.3	60
> 20.5 sound	40.9	31.8	30
Total wood debris	83.0	65.4	25
Total aboveground fuel	98.7	68.1	40
Ash		2.0	

* These data are from the second fire in the pasture phase of this site and the third fire on this site since deforestation. The site was deforested, slashed burned, and planted directly to pasture. After 2 years the site was reburned.

Photo 55. Livestock pasture prior to burning, Santa Barbara, Jamari, Rondonia (Table 3 18). While this site had been utilized for shifting cultivation through two cycles, this was the first fire to occur on this site after pasture formation. However, 3 slash fires had previously occurred on this site. The site had not been utilized by cattle prior to burning (photo by R. F. Hughes).

Photo 56. Livestock pasture following burning, Santa Barbara, Rondonia. A significant rainfall event prevented collection of ash following burning and likely depressed the consumption of wood fuels (photo by R. F. Hughes).

Table 3.18. AMAZONIA - LIVESTOCK PASTURE - 4TH YEAR SINCE PRIMARY DEFORESTATION

Site Location: Santa Barbara, Rondonia Cite: Hughes (In prep.)

Burn Date: September 1993 [50% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter*	19.5	4.0	80
Dicot seedlings	0.0	0.0	–
Wood debris (cm in diam.)			
0 - 0.64	0.2	0.1	46
0.65 - 2.54	1.6	0.6	58
2.55 - 7.62	1.1	0.8	25
7.63 -20.5 sound	4.4	3.7	16
rotten	1.0	0.8	19
> 20.5 sound	31.7	21.3	33
Total wood debris	40.1	27.4	32
Total aboveground fuel	59.5	31.4	47

* This site was converted from primary forest to shifting cultivation 14 years prior to sampling. The site had experienced 2 cultivation/fallow cycles. Crops included rice, corn, and manihot. Site was subsequently cut and burned for conversion to pasture 2 years prior to sampling. Data presented here were from a fire utilized to promote increased productivity and nutrition of pasture grasses.

Photo 57. Livestock pasture prior to burning, Maraba, Para (Table 3.19). Note the dry nature of fuels compared to the other pastures in this series. An abundance of slashed palm fronds greatly contributed to the litter fuel load at this site (photo by J. B. Kauffman).

Photo 58. Livestock pasture following burning, Maraba, Para. The very high consumption rate of this site is attributed to the dry conditions at the time of burning as well as a proportionately high quantity of fine fuels (photo by J. B. Kauffman).

Table 3.19. AMAZONIA - LIVESTOCK PASTURE - 12 YEARS SINCE PRIMARY
DEFORESTATION*
Site Location: Maraba, Para Cite: Kauffman and Cummings (1995a)
Burn Date: September 1991 [81% Total Fuel Consumption]

| Component | FUEL LOADING (Mg ha⁻¹) | | COMBUSTION FACTOR |
	Prefire	Postfire	(%)
Litter	23.6	0.0	100
Live grass	4.2	0.0	100
Dicot seedlings	1.5	0.0	100
Wood debris (cm in diam.)			
0 - 0.64	0.6	0.1	83
0.65 - 2.54	2.5	0.4	84
2.55 - 7.62	4.2	0.8	80
7.63 -20.5 sound	6.7	2	71
rotten	0.4	0.0	100
palms	1.4	0.0	100
> 20.5 sound	8.2	5.3	36
rotten	1.3	0.0	100
Total wood debris	25.4	8.5	67
Total aboveground fuel	53.3	8.8	81
Ash		4.8	

* This site had been utilized as shifting cultivation following deforestation of the primary forest. Following
fallow, the second-growth forest was cut and the site was converted to pasture. This was the first fire during
the pasture phase of management.

Photo 59. Livestsock pasture prior to burning, Jamari, Rondonia (Table 3.20). In sites such as this, with a long land use history, residual wood is typically very dense and resistant to both decomposition and combustion (photo by J. B. Kauffman).

Photo 60. Livestock pasture following burning, Jamari, Rondonia. Note persistence of large wood fuels (photo by J. B. Kauffman).

Table 3.20. AMAZONIA - LIVESTOCK PASTURE - 10TH YEAR SINCE PRIMARY
DEFORESTATION*
Site Location: Jamari, Rondonia Cite: Kauffman and Cummings (1995a)
Burn Date: September 1992 [68% Total Fuel Consumption]

	FUEL LOADING (Mg ha⁻¹)		COMBUSTION FACTOR
Component	Prefire	Postfire	(%)
Litter	16.9	0.3	95
Live grass	2.5	0.1	98
Dicot seedlings	0.1	0.0	100
Wood debris (cm in diam.)			
0 - 0.64	0.0	0.0	-
0.65 - 2.54	0.3	0.2	33
2.55 - 7.62	0.3	0.1	66
7.63 -20.5 sound	6	5.7	19
rotten	1.0	0.6	45
> 20.5 sound	45.5	31.4	32
Total wood debris	53.1	37.9	37
Total aboveground fuel	72.7	38.2	68
Ash	--	3.0	

* This site had undergone 2 shifting cultivation cycles prior to conversion to livestock pasture. Therefore, the land use history of this site includes: (1) a primary slash fire; (2) a slash fire of second-growth forest fallow; (3) a slash fire of third-growth forest fallow; and (4) the pasture fire.

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III. Biomass, nutrient pools, and losses in cattle pastures of the Brazilian Amazon

ABSTRACT

Conversion to cattle pasture is the most common fate of the ~426,000 km^2 of the

Brazilian Amazon that has been deforested. Because of changes in ecosystem structure and

processes over the large area they encompass, these sites may have important influences on

climate, biogeochemical and hydrological patterns at regional and global scales. Yet little is

known on the dynamics of C and other nutrient pools associated with the frequent fires that

occur in these pastures. We sampled biomass, nutrient pools and influences of fire in three

Amazonian cattle pastures with typical, but different land use histories. Total aboveground

biomass (TAGB) of cattle pastures ranged from to 53 to 119 Mg ha^{-1}. Residual wood debris

from the forests that formally occupied the sites comprised the majority of TAGB (47-87%).

Biomass of fine fuels, principally pasture grasses, was ~16 to 29 Mg ha^{-1}. However, grasses

contained as much as 52% of the aboveground K pool and the grass and litter components

combined comprised as much as 88% of the aboveground P pool. Fires consumed from 21 to

84% of the TAGB. Losses of C to the atmosphere ranged from 11 to 21 Mg ha^{-1} and N losses

ranged from 205 to 261 kg ha^{-1}. Losses of S, P, Ca, and K were <33 kg ha^{-1}. While only 3-

4% of the C pool remained in the ash component following fire, >82% of the aboveground

pool of Ca and K was found in ash following fire.

While large losses in TAGB occurred as a result of forest conversion to pasture, we

found no increase in surface soil (0-10 cm) nutrient concentration in pastures when compared

to adjacent primary forests. The biomass of C in ecosystem pools comprised of surface soils

and TAGB in pastures can be reduced to 22% of that of the primary forest they replaced.

Given the prevalence of pasture conversion, the associated high frequency of fires that occur in

converted pastures, and the resulting transfer of nutrients to the atmosphere via combustion

processes, they are likely significant influences on global biogeochemical cycles.

KEYWORDS: Cattle pastures, deforestation, nutrient cycling, biomass burning, tropical

forests, carbon cycling

INTRODUCTION

An estimated 426,000 km^2 of forests have been cleared in the Brazilian Amazon by 1991 (Fearnside 1993a. 1993b). Annual rates of deforestation ranged from 15,200 to 19,900 km^2 yr^{-1} from 1978 to 1988 and from 11,000 to 19,000 km^2 yr^{-1} since that time (Fearnside 1993b, Skole and Tucker 1993). The dominant land use resulting in forest clearing has been cattle pasture formation (Fearnside 1988, Uhl et al., 1988). Fires are utilized for both the formation and maintenance of cattle pastures. Because of the areal extent and frequency of burning, pasture fires are potentially significant sources of CO_2 and other greenhouse gasses.

While estimates of aboveground biomass and C pools of intact Amazon forests are available (e.g., Brown and Lugo 1992, Fearnside et al. 1993, Kauffman et al. 1995), few studies have quantified these parameters in cattle pastures. Uhl and Kauffman (1990) reported that the total aboveground biomass (TAGB) of an old cattle pasture in the eastern Amazon was 52 Mg ha^{-1}. In addition, a paucity of information exists on the quantification of the effects of pasture fire on TAGB and nutrient pool dynamics. Fire effects have been reported in slash fires in Brazilian dry forest (Kauffman et al. 1993), Brazilian savannas (Kauffman et al. 1994) and in the Brazilian Amazon (Fearnside et al. 1993; Kauffman et al. 1995). In slashed primary forests of Amazonia, Kauffman et al. (1995) reported that TAGB ranged from to 290 to 435 Mg ha^{-1}; ~50% of the TAGB was consumed by fire. Similar studies do not exist for pastures fires in the Brazilian Amazon.

Patterns of land use are variable in the Brazilian Amazon (Fearnside 1988). Following the initial slash fires, lands are often converted directly to pasture or they may be used in shifting cultivation prior to conversion. Upon establishment of the pasture, fires are set by

local landowners every 2-3 years to favor dominance of pasture grasses over invading or residual vegetation as well as to enhance the palatability and growth of grasses (Uhl et al. 1988; Fearnside 1992). Accidental fires are also extremely common in Amazonian regions of extensive deforestation (Uhl and Buschbacher 1985). Pasture fires are now likely to be the most prevalent type of fire in the Brazilian Amazon. As a result, it is important to quantify the dynamics associated with biomass, nutrient pools, and fires in these pastures. In three Amazon cattle pastures with varying land use histories and time periods since establishment the objectives of this study were to: (1) quantify TAGB and the quantities consumed by fires; (2) quantify the nutrient pools in aboveground biomass and soil surface; (3) quantify losses and redistribution of nutrient pools as a result of fire; and (4) compare the mass of nutrient pools in pastures with those of adjacent primary forests.

METHODS

Study Area

The study areas were located in the Brazilian states of Rondonia and Para. These are areas of the Brazilian Amazon that have been, and currently are undergoing rapid rates of deforestation (Skole and Tucker 1993, Fearnside 1992). The intact primary forests of these areas are classified as Floresta Tropical Perenifolia de Terra Firme (upland tropical evergreen forest) by Eiten (1983) or as Floresta Ombrofila densa-submontana (Para) and Floresta ombrofila aberta submontana (Rondonia) (i.e., dense and open submontane tropical forests) by the Radam project (Brazil, Projeto RADAMBRASIL, 1976,1978). Total aboveground biomass of forests in the proximity of the sampled pastures in this study were 292 and 435 Mg ha^{-1} in the Para site and 290 and 361 Mg ha^{-1} in the Rondonia sites (Kauffman et al. 1995).

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In this study, we sampled three pastures with different land use histories. We refer to the individual pastures in this study by the names of the land owners. We interviewed each land owner to obtain information on the land use history and future management objectives of the particular pasture. The first pasture (Francisco) was sampled in 1991. This site is approximately 50km south of the city of Maraba, Para (~5 21'S, 49 09'W). The primary forest of this site had been felled approximately 12 years prior to the onset of this study. Initially, the site had been utilized as a cooperative farm under intensive cultivation. Following abandonment, the present owner cut the second-growth forest and converted the site to pasture. The results reported here are from the first pasture fire which occurred three years after the second growth forest had been cut. However, there were at least two slash fires (the primary forest and the second- growth forest) prior to this fire. Additionally, following these slash fires much of the residual wood debris had been piled and burned.

The second and third pasture sites (Durval and Joao) were sampled near the town of Jamari, Rondonia in 1992 (~9 12'S, 60 3'W). The Durval pasture had been formed from primary forest 4 years prior to the onset of this study. This site had previously experienced the slash fire of the primary forest and a pasture fire 2 years following deforestation. Results from the second pasture fire are reported here. The Joao pasture site had been formed from a third-growth forest two years prior to this study. While this was the first pasture fire on this site, it had undergone two cycles of shifting cultivation prior to pasture formation. Prior to this fire, the site had been burned three times (a primary slash fire, a second-growth slash fire, and a third-growth slash fire). Following these slash fires, residual slash that could be carried by hand was piled and burned prior to planting.

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Climatological data from the nearest stations are from Maraba, Para and Porto Velho, Rondonia. Mean average precipitation of the two stations is 2088 and 2354 mm, respectively. A pronounced dry season exists from June to September with precipitation normally <100 mm during these months. Mean average temperatures are 26° C and 25° C, average minimum temperatures are 22° C and 20° C, and average maximum temperatures are 31° C and 31° C, and mean relative humidity is 82% and 85%, respectively (Departamento Nacional de Meteorologia, Brasil 1992).

All sites were burned towards the end of the dry season (late August and September. The pastures were burned utilizing circle-fire ignition patterns where the entire perimeter is ignited causing the fire to burn most intensely towards the center. Typically sites were ignited when diurnal temperatures were warmest and relative humidity lowest (1200 to 1400 h).

Aboveground Biomass

We partitioned the aboveground biomass on the basis of plant morphology, influences on fire behavior, value as a nutrient pool, and limitations of the sampling approach. TAGB categories include litter (dormant grass, dead leaves, slashed palm fronds and all other non-wood organic materials), green grass, dicots (sprouts and seedlings), and residual wood debris from primary or secondary forests.

The prefire mass of residual wood debris, the amounts consumed by fire, and the postfire mass of residual wood debris were estimated nondestructively utilizing planar intersect models modified specifically for each pasture (Brown and Roussopoulous 1974; Van Wagner 1968). At each site, 32 planar intersect transects were systematically established to ensure sample dispersion through the pastures. All transects were marked with small aluminum stakes

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prior to burning. This facilitated exact relocation and remeasurement following fire. Diameters of all wood particles intersecting each sample plane were measured. We partitioned the wood debris into standardized size classes based on their diameter. Wood particle diameter is a good predictor of the rate of moisture loss (i.e., the time-lag constant) and hence relationships to combustion and fire behavior (Deeming et al. 1977). These diameter size classes have also been shown to vary inversely with nutrient concentrations and improve calculations of loss or redistribution by fire (Kauffman et al. 1993; Kauffman et al. 1994). The diameter classes used to partition wood debris were the same as those utilized in slashed Amazonian primary forest by Kauffman et al. (1995): 0 to 0.65 cm diam, 0.64 to 2.54 cm diam., 2.55 to 7.5 cm diam., 7.6 to 20.5 cm diam., and >20.5 cm diam. For wood particles >7.5 cm diam., we further separated them into sound and rotten classes. Wood debris from palms were separated from other trees. Lengths of the sampling plane varied among the wood debris size classes: 1 m for wood particles ≤0.64 cm diam., 2 m for wood debris 0.65 to 2.54 cm diam., 5 m for wood debris 2.55 to 7.6 cm diam., and 15 m for the coarse wood (i.e., logs >7.5 cm diam.). The diameter of each coarse wood debris particle intercepting the plane was measured to the nearest half centimeter. For the three wood debris size classes ≤7.5 cm diam., a quadratic mean diameter was utilized for equations through measurement of 100 particles of each size class at each site. Thereafter, for these classes we counted the number of particles that intersected the sampling plane. Bias due to fuel particle tilt and slope was corrected for as outlined in Van Wagner (1968) and Brown and Roussopoulous (1974). Thirty randomly collected samples of each size class were measured for specific gravity (particle density) at each site.

The biomass of litter, grass, seedlings, and sprouts were destructively sampled through collection of all materials in 25 x 25 cm microplots. A microplot was placed at the 2 m mark of each planar intersect transect (i.e., n = 32 plots per site). The mass of litter, green grass, and dicots within each microplot was separated, oven dried and weighed. Following fire, postfire mass of these components was collected from another microplot established 2 m away from the prefire microplot.

Ash mass at the Francisco site was manually collected by gently sweeping all ash in the postfire microplot into paper bags. At the Durval and Joao sites, ash mass was determined through collection within sixteen 50 x 50 cm microplots. A portable electric generator and vacuum cleaner was utilized to collect the ash within each microplot. The ash from each microplot was oven dried and weighed to determine mass.

Nutrient Pools –

Aboveground nutrient pools were partitioned into the same classes as aboveground biomass. Prior to burning, five samples of each fuel component were collected at each site. Each of these samples consisted of a composite mix of 10-20 collections of materials. Ash samples were collected in the same manner following fire. At each site five soil samples at depths of 0-2.5 cm and 2.5-10 cm were also collected. Following fires at the Francisco site, soils were re-sampled approximately 1 m away from the prefire soil sampling areas. Five samples to determine soil bulk density were collected in the same areas as nutrient samples. All samples were air-dried for at least one week, placed in plastic bags and transported to the laboratory for nutrient analysis.

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All plant and ash samples were analyzed for total N, P, K, C, S and Ca. Soils at the Durval and Joao site were also analyzed for these elements. However, only C and N were analyzed in soils from the Francisco site.. Prior to analysis, plant and ash samples were ground to pass through a 40 mesh screen (0.5 mm) in a Wiley mill. Total N was determined from Kjeldahl digestion (Bremner and Mulvanay 1982). Total Ca, K, and S were determined by atomic absorption (Tabatabai and Bremner 1970). Total P was determined colorimetrically following wet digestion utilizing a Kjeldahl procedure (Watanabe and Olsen 1965). Total C was analyzed by the induction furnace method (Perkin-Elmer 2400 elemental analyzer for the Francisco site and a Carlo-Erba NA Series 1500 for the Durval and Joao sites) (Nelson and Sommers 1982). Organic matter of ash from the Durval and Joao sites was determined through complete combustion of samples at 500° C for 8 hours in a muffle furnace (Davies 1974).

To determine influences of pasture conversion on nutrient pools relative to those of primary forests, the pastures in this study were paired with primary forests. The primary forest nutrient pools were described in detail by Kauffman et al. (1995). The Francisco pasture was adjacent to the Maraba forest site; the Durval pasture was adjacent to the Jamari forest site; and the Joao pasture was approximately 5 km from the Santa Barbara forest sites.

Fire Behavior and Fuel Conditions

Fuel moisture content, air temperature, relative humidity, and flame length were recorded at each site prior to, and during the flaming phase of combustion. Moisture content (dry-weight basis) at the time of ignition was calculated through collection of 5-10 samples of the following components: soil surface, dead grass, live grass, dicots, and wood > 7.6 cm

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diameter. Samples were weighed in the field with a portable digital balance. They were then oven dried at 60°C for 5 to 7 days to calculate dry weight. Air temperature and relative humidity at the time of ignition was measured on site with a sling psychrometer; wind speed was measured with a portable anemometer.

Differences in nutrient pools, postfire nutrient pools, ash and nutrients lost from the site were tested between the pastures through analysis of variance in a completely randomized design. If significant, the least significant difference multiple range test was utilized to determine statistical significance among the sites sampled (P $\leq$ 0.10)

RESULTS

Aboveground Biomass

Total aboveground biomass ranged from 53 Mg ha^{-1} at the Francisco site with a long, intensive land use history to 119 Mg ha^{-1} at the relatively recently established pasture site of Durval (Table 1). Wood debris from the primary forests comprised ~87% of the TAGB at the Durval pasture and 73% at the Joao pasture. Wood mass remained a dominant component at the Francisco pasture comprising 47% of the TAGB. In the chronology from the youngest to the oldest pasture, the mass of the coarse wood legacy (>7.6 cm diam.) was 97 Mg ha^{-1} at the Durval pasture, 53 Mg ha^{-1} at the Joao pasture, and 18 Mg ha^{-1} at the Francisco pasture.

The biomass of all herbaceous materials combined was 29, 15, and 19 Mg ha^{-1}, at the Francisco, Durval, and Joao pastures, respectively. This component was most prevalent at the Francisco pasture which had not been burned in three years as opposed to two years for the other pastures. In addition, there was a significant amount of slashed palm fronds that contributed to the high mass of litter (24 Mg ha^{-1}) on this site.

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Fire and Fuel Conditions

All fires were conducted towards the end of the dry season, following 2 to 7 rainless days (Table 2). Air temperature during the three pasture fires ranged from 30 to 34° C and relative humidity ranged from 38 to 55%. Dead grass which is the ecosystem component that facilitates sustained ignition and fire spread in pastures had a moisture content of 2.7 and 6.0% at the Joao and Francisco sites, respectively. In contrast live grass moisture content was 225 and 209% in these areas.

Flame lengths of these pasture fires were highly variable ranging from 0.5 to 4m at all sites (Table 2). Flaming combustion was short-lived; total pasture coverage of the fire always required <2 hours. However, smoldering combustion of residual wood debris often lasted for >3 days.

Among pastures, the levels of total aboveground biomass consumed by fire (the combustion factor) was highly variable (Table 1). Total biomass consumption ranged from 21% at the Durval pasture to 84% at the Francisco pasture. After burning, the TAGB which largely consisted of residual uncombusted wood debris ranged from 8.8 Mg ha^{-1} at the Francisco pasture to 94.7 Mg ha^{-1} at the Durval pasture. Virtually all (>96%) of the fine herbaceous fuels were consumed by fire. In contrast, consumption of wood debris by fire was 9% at the Durval site and 29% at the Joao site. However, dry conditions and a greater composition of fine wood fractions resulted in a wood consumption rate of 66% at the Francisco site. Sound wood debris >20.5 cm diam.) were typically widely scattered throughout the sites. This component represented that fraction of the primary forest wood component most resistant to both decomposition and consumption. Given the arrangement and

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high wood density of this component, consumption was only 1% at the Durval pasture, 31% at the Joao pasture and 36% at the Francisco pasture (Table 1). In addition to residual wood, ash was the only other significant postfire aboveground nutrient or organic matter pool. Ash mass ranged from 2.1 to 4.8 Mg ha^{-1}.

Aboveground Nutrient Pools

While we sampled nutrient concentrations of all sites separately, only the mean nutrient concentrations of all sites combined are given in Table 3. Concentrations of all nutrients (except C) were typically highest in the grass and dicot components of the pastures (Table 3). In contrast to other nutrients, the concentration of C was slightly lower in grass and litter fractions (~46%) compared to dicot and wood fractions (~50%). Concentrations of other nutrients within wood debris declined with increasing diameter. Palm trunks had dramatically higher concentrations of N, S, P, and K than sound coarse wood debris of dicotyledonous taxa. For example, concentration of K in palm trunks was almost 19-fold greater than the coarse wood debris (15.42 and 0.82 mg g^{-1}, respectively). Concentration of K in palm trunks was similar in concentration to that of the pasture grasses (Table 3).

The concentration of nutrients in ash was much different than that of uncombusted debris (Table 4). The concentration of C which is readily volatilized was 17 to 20% in ash. N concentration in ash ranged from 4.2 to 8.9 mg g^{-1} as compared to a mean concentration of 5.1 to 5.7 mg g^{-1} in fuels (Table 5). Concentration of those nutrients with high temperatures of volatilization were much higher in ash as compared to unburned debris. For example mean concentration of Ca in TAGB prior to burning was 0.9 to 3.0 mg g^{-1}; concentration of Ca in ash ranged from 16.8 to 49.0 mg g^{-1}.

Differences in ash nutrient concentrations among sites tended to reflect the influences of site differences in tissue nutrient concentration as well as the influences of variable levels of biomass consumption by fire (Table 4). At the Francisco site, (the pasture with the highest combustion factor) ash concentrations of readily volatilizable nutrients (N and C) were lower and nutrients with a high temperature of volatilization (P, K, and Ca) were higher.

Total aboveground pools of C were 26 to 59 Mg ha^{-1} or ~50% of the TAGB (Table 5, Figure 1). Total aboveground N pools were 304 to 661 kg ha^{-1}; aboveground pools of K were 122 to 221 kg ha^{-1}; aboveground pools of Ca were 84 to 162 kg ha^{-1}; aboveground pools of S were 42 to 78 kg ha^{-1}; and aboveground pools of P were 11 to 30 kg ha^{-1}. Because the concentration of C did not vary greatly between fuel components, the relative distribution of C was similar to that of the TAGB. However, a disproportionate quantity of the pools of other nutrients was found in the smaller fuel particles, particularly grasses and litter. For example, while grass only comprised 3.5% of the TAGB at the Joao site (Table 1), 51.5% of the aboveground pool of K was sequestered in this component (Fig 1). At this site, the grass and litter components combined comprised 27% of the TAGB but comprised 87.6 % of the total aboveground P pool.

Fire Effects on Nutrient pools

As a result of fire, nutrient pools were either lost from the site via volatilization and aerosol transport, transformed from an organic pool into ash, or remained unaffected in residual uncombusted debris (Table 5, Figure 1). Nutrient responses appeared to be strongly influenced by three fire or ecosystem factors: (1) levels of biomass consumption; (2) nutrient distribution within the fuel classes influencing susceptibility of combustion losses; and (3)

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temperatures of volatilization of nutrients. The combination of a low temperature of volatilization as well as a disproportionate concentration in fine fuels which were consumed in very high percentages resulted in high site losses for N. Site losses of N were consistently higher than the quantity of biomass consumed by fire. Site losses of N ranged from 205 to 261 kg ha^{-1} or 36 to 86% of the prefire aboveground pool. In contrast, even though higher concentrations of K and Ca were found in grasses and litter (of which >96% were consumed by fire), low quantities were actually lost from the site. Losses of Ca and K were <15% and 22% of the prefire aboveground pool, respectively. Losses of P ranged from 1 to 37% of the prefire aboveground pool. Losses of S were intermediate to the relatively low losses of these cations and the high losses of N. S losses were 24 to 52% of the prefire aboveground pool.

Only 3 to 4% of the prefire C pool was transformed into the ash component by fire. Losses of C as a result of fire ranged from 11 Mg ha^{-1} at the Durval site to 21 Mg ha^{-1} at the Francisco site. This represented 19 and 81% of the prefire aboveground C pools, respectively.

While <4% of the prefire C and N pools were transformed into the ash component, larger proportions of the postfire pools of those nutrients with high temperatures of volatilization were found in the ash component following fire (Table 5, Figure 1). This was particularly true at the Francisco site where >82% of the prefire nutrient pool of Ca and K was found in the ash component following fire. The differences in the level of biomass consumption among sites influenced the partitioning of nutrients in postfire aboveground pools (Figure 1). For example, at the Francisco site which had a combustion factor of 84%, >82 % of the postfire pools of S, P, K, and Ca were found in the ash component. In contrast, at the Durval site with a relatively low combustion factor (21%), <37% of the residual postfire

nutrient pool of S, P, and Ca was in ash. Because large quantities of K were sequestered in

the grass/litter component of which virtually all was consumed by fire, ash always comprised a

large proportion of the postfire K pool. The remainder not found in ash was largely

sequestered in residual wood debris. The variable fate of nutrients among the three sites

indicates that fire severity will not only influence nutrient losses during the combustion event,

but following the fire as well. As ash is much more mobile in the ecosystem than residual

uncombusted wood debris, it is likely that greater site losses via erosion processes would

occur in sites with high combustion factors such as the Francisco site as compared to sites with

low combustion factors such as the Durval site.

Soil Nutrient Pools

Nutrient concentrations of soils are indicative of the oligotrophic nature of the Oxisols

underlying these pastures (Table 6). Concentrations at the 0-2.5 cm layer were consistently

higher than those of the 2.5-10 cm layer. Concentration of N, C, S, and P were highest in the

recently established Durval pasture as compared to the older Francisco and Joao pastures. In

contrast, K and Ca were higher in the 0-2.5 cm depth of the Joao pasture as compared to the

Durval pasture. This may be reflective of the cumulative influence of nutrient inputs from ash

following numerous slash and pasture fires as well as litter inputs from pasture grasses which

were higher in K than wood debris or litter from primary forest (Kauffman et al. 1995). With

the exception of C, nutrient concentrations of soils were much lower than that of ash (Tables 4

and 7). Following fire, slight increases of N and C concentration were measured in soils at the

Francisco site.

The bulk density of soils ranged from 1.28 to 1.34 gm cm^{-3}. Nitrogen and C mass in the top 10 cm soil layer ranged from 2513 to 3659 kg ha^{-1} and from 32.2 to 52.1 Mg ha^{-1}, respectively (Table 7). Carbon at the 10-30 cm depth at the Francisco site was 20.7 Mg ha^{-1} or ~30% of the entire soil C pool to 30 cm. In the 0-10 cm soil surface layer of the Durval and Joao, Rondonia pastures, S mass was 344 and 299 kg ha^{-1}, P mass was 188 and 165 kg ha^{-1}, K mass was 131 and 194 kg ha^{-1} and Ca mass was 345 and 431 kg ha^{-1}. The 0-2.5 cm surface layer comprised >30% of the 0-10 cm soil nutrient pool of N, C, S, and P. At the Joao site the K and Ca pool in the 0-2.5cm layer exceeded that of the 2.5-10cm layer. This was unlike that of the Durval pasture (Table 7).

The mass of N, P, and Ca in soil pools exceeded that of pools sequestered in TAGB (Tables 5 and 7, Figure. 1). For example, aboveground N pools only accounted for 10 to 15% of the ecosystem pool comprised of TAGB and the 0-10cm surface layer of soils. Aboveground P pools comprised 6 to 11% of the total P pool. In contrast, C and K pools were approximately equivalent between these aboveground and belowground components. Aboveground C comprised 41 to 53% of these ecosystem pools. As a proportion of this ecosystem pool, fires resulted in the loss of 6 to 9% of N, 10 to 34% of C, 4.5 and 4.7% of S, 2.4 and 0.06% of P, 11.7 and 6.6% of K, and 3.5 and 1.9% of Ca.

DISCUSSION

Biomass and Nutrient Losses By Pasture Fires

The TAGB of pastures in this study (53-119 Mg ha^{-1}) is similar to that reported for an old cattle pasture in the eastern Amazon (52 Mg ha^{-1}) (Uhl and Kauffman 1990). In contrast, biomass of fuels in Brazilian tropical savannas (Cerrado) ranged from 7 to 10 Mg ha^{-1}

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(Kauffman et al. 1995). The great differences in biomass between Amazonian cattle pastures and naturally occurring tropical savannas are due principally to the residual wood debris. Similarly, the C and other nutrient losses arising from fires in cattle pastures are dramatically higher than that of natural savanna fires. For example, C losses were 2.6 to 3.2 Mg ha^{-1} in Cerrado fires compared to 11 to 21 Mg ha^{-1} for pasture fires (Table 5, Kauffman et al. 1994). N losses from fire in Amazonian cattle pastures were ˜10-fold greater than losses from fires in these natural savannas.

The loss of nutrients from fires in the Amazon will vary greatly depending upon the particular land use in question. Biomass and nutrient losses from fires in Amazon cattle pastures are substantially lower than that of fires in slashed primary forests. The mean biomass loss from primary slash fires was 172 Mg ha^{-1} compared to the mean biomass loss in pasture fires of 35 Mg ha^{-1} (Table 1, Kauffman et al. 1995).

C Inputs Into The Atmosphere By Pasture Fires

Virtually all deforested areas are eventually converted to pasture in the Amazon; large ranchers normally convert deforested areas directly to pasture and small landowners typically utilize areas in one or two shifting crop rotations prior to pasture conversion. Fires are the most common means of pasture maintenance. Based upon our interviews with landowners we found that pastures are purposefully burned on the average of every 2 or 3 years for the first 10 y of the pasture's existence. Uhl et al. (1988) and Fearnside (1992) also reported that moderate to heavily utilized pastures with a lifetime of 6 to 12 years were reburned 1 to 5 times. Because of the widespread use of fire for all aspects of pasture management and forest slash disposal, accidental fires are commonplace in the Amazon (Uhl and Buschbacher 1985).

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We have observed that approximately 40% of the fires set in slash and pastures escaped into adjacent areas of pasture, cropland, or slash.

The contribution of pastures fires as a source or sink of greenhouse gasses is largely unknown. Fearnside (1992) suggested that under a typical scenario of three fires following the initial slash fire a total of 35% of the biomass C would be released from combustion processes and 61.9% would be released through decomposition processes. Kauffman et al. (1995) reported that the mean combustion factor of four primary Amazon slash fires was 50%. The mean TAGB of these forests were 345 Mg ha^{-1}. Based upon the mean biomass loss of the three pasture fires in this study we estimate that 3 reburns in a pasture would consume ~41 Mg ha^{-1} of residual wood originating from the forest. This is equivalent to a total release of 12% of the forest TAGB. Therefore, the total biomass consumed in the initial fire and the three pasture fires is estimated to equal 276 Mg ha^{-1} or 62% of the mean TAGB of primary forests. Our results indicate that more C is released via combustion processes and less is released via decomposition processes than what was predicted by Fearnside (1992).

As pasture burns are the most common types of fire currently occurring in the Amazon, they are likely to be significant sources of C to the atmosphere. If the deforestation rate is ~15,000 to 19,900 km y^{-1} in the Amazon (Skole and Tucker 1993, Fearnside 1993b) and pastures fires are set (or accidentally burned) on the average of every two years, then pastures fires may burn on 60,000-80,000 km^2 of land in a given year in the Amazon. With a mean C loss of ~16 Mg ha^{-1} in pastures (Table 5), pastures fires covering this area would result in C inputs of 96 to 128 Tg y^{-1} into the atmosphere. Mean C losses by primary slash fires (~86 Mg ha^{-1}) was reported by Kauffman et al.(1995). If deforestation rates are 15,000 to 19,900 km^{-1}, C losses associated with

the initial primary forest slash fires would total 130 to 160 Tg y^{-1}. Our data in concert with

remotely sensed data of deforestation rates, clearly indicate that pasture fires are a significant C

source with respect to atmospheric inputs.

<u>Response of Nutrient Pools to Conversion From Forest to Pasture</u>

While there are significant losses in aboveground pools upon the conversion of forests

to pastures, the influences of belowground pools are not so clear. C concentration of surface

soils in pastures ranged from 3.55 to 5.78% (Table 6) compared to 3.01-6.27% for paired

primary forests of the same regions (Kauffman et al. 1995). Comparison of the soil pools of C

is complicated by the increase in bulk density following conversion to pasture (a mean of 1.31

g cm^3 in pastures and 0.90 g cm^3 in primary forests). To compensate for differences in bulk

density, we compared belowground C pools in pastures and forests on the basis of soil mass.

Belowground C pools in Fig 2 are based on the equivalent mass of soils of the 0-10 cm layer

in primary forests (1069 and 750 Mg ha^{-1} for the Para and Rondonia sites, respectively).

When forests are converted to pastures dramatic shifts in the partitioning of ecosystem

nutrient pools occur. In primary forests aboveground pools of C and K comprised ~76-89% of

the ecosystem pool and above ground pools of N and S were approximately equivalent to

belowground pools. Soil P comprised ~35% of the ecosystem pool (Fig 2). With a

significant loss in aboveground pools and minimal gains or losses in belowground pools, large

shifts in the partitioning of nutrient pools to belowground stocks occurred with pasture

conversion. This was particularly true of the older Santa Barbara and Joao pastures where

greater quantities of residual logs from the forest had disappeared.

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When forests are converted to pastures dramatic shifts in the partitioning of ecosystem nutrient pools occur. In primary forests aboveground pools of C and Ca comprised ~76-89% of the ecosystem pool and above ground pools of N and S were approximately equivalent to belowground pools. Soil P comprised ~35% of the ecosystem pool (Fig 2). With a significant loss in aboveground pools and minimal gains or losses in belowground pools, large shifts in the partitioning of nutrient pools to belowground stocks occurred with pasture conversion. This was particularly true of the older Santa Barbara and Joao pastures where greater quantities of residual logs from the forest had disappeared.

Comparing ecosystem pools of nutrients between the pastures and the paired forests we found that C pools of pastures were 22 to 43% of those in forests; N pools in pastures were 44 to 59% of those in forests; S pools were 49 to 52% of those in forests; K pools were 35 to 44% of those found in forests; P pools were 63 to 83% of those found in forests and Ca pools in pastures were 31 to 84% of those in forests (Fig 2).

With the exception of Ca, we did not find any dramatic losses or gains in belowground pools when comparing pastures to primary forest sites (Fig 2). The concentration and the relative mass of Ca was higher in soils of pastures than in the primary forest. Apparently, greater proportions of Ca deposited as ash or released through root decomposition are retained in soils than other nutrients.

Data in Figure 2 are the prefire pools of nutrients in pastures. Because almost all of the wood was consumed by fire, the postfire aboveground C pool in the Francisco pasture was ~3.4% of the C pool in the adjacent primary forest (i.e, the Maraba site in Kauffman et al.

1995). This small aboveground C pool is likely the ultimate fate of C pools in pastures under the current land management scenarios in the Amazon.

Agricultural and cattle ranching activities are unsustainable as practiced and unlikely to be converted into sustainable systems on sufficiently wide areas (Fearnside 1988, 1993a). In ecological, societal, and economic contexts, there are a number of negative ramifications associated with deforestation and conversion to pasture. Dramatic losses in biological diversity, and site productivity occurs with increases in soil erosion, and compaction. Pasture conversion does not require a large labor force and does little to alleviate employment shortages in rural areas of Amazonia (Fearnside 1993a). Repeated pasture fires are significant sources of atmospheric C and other greenhouse gasses. Cumulatively over the life of a pasture, atmospheric inputs of radiatively active gasses arising from pasture fires are likely to be equivalent to that of the slash fires of primary forests. Given current landuse patterns, fires burn more areas in this cover type in the Amazon than any other. A better quantification of the global contribution of greenhouse gasses from pasture fires and the concomitant influences of nutrient depletion of these systems to sequester C and/or provide sustainable resources is imperative.

ACKNOWLEDGMENTS

FIGURES

Figure 2. Ecosystem pools of primary forests and slash fires. These nutrient pools are comprised of the total aboveground biomass and surface soils. Soil nutrient pools are representative of equivalent amounts of soils in pastures and primary forests. This is the mass found in the top 10 cm of soils in primary forests. As soil bulk density is higher in pastures, pools reported in this figure are lower than those of Table 7.

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Table 1. Total aboveground biomass (Mg ha^{-1}) prior to, and following biomass burning in cattle pastures of Para and Rondonia, Brazil. Numbers are mean $\pm$ standard error.

	Francisco-Para		Durval-Rondonia		Joao-Rondonia	
	Prefire	Postfire	Prefire	Postfire	Prefire	Postfire
Litter/dead grass	23.65 ± 2.37	0.03 ± 0.02	11.62 ± 1.21	0.09 ± 0.04	16.95 ± 1.61	0.27 ± 0.19
Grass	4.24 ± 3.19	0.00 ± 0.00	3.76 ± 0.67	0.46 ± 0.17	2.55 ± 0.52	0.07 ± 0.04
Dicots	1.50 ± 0.52	0.24 ± 0.15	0.30 ± 0.30	0.00 ± 0.00	0.10 ± 0.10	0.01 ± 0.01
Wood Debris (diam cm)						
0-0.64	0.60 ± 0.18	0.05 ± 0.05	0.13 ± 0.10	0.00 ± 0.00	0.01 ± 0.01	0.01 ± 0.01
0.65-2.54	1.51 ± 0.57	0.41 ± 0.23	0.37 ± 0.26	0.52 ± 0.42	0.26 ± 0.11	0.79 ± 0.05
2.55-7.6	4.20 ± 0.88	0.84 ± 0.28	6.12 ± 1.51	4.40 ± 1.42	0.27 ± 0.15	0.09 ± 0.09
7.6-20.5 sound	6.73 ± 1.83	1.96 ± 0.72	37.36 ± 7.74	29.73 ± 6.34	5.99 ± 1.33	5.71 ± 1.55
7.6-20.5 rotten	0.36 ± 0.22	0.00 ± 0.00	1.64 ± 1.04	2.03 ± 1.06	1.00 ± 0.48	0.58 ± 0.41
>20.5 sound	8.24 ± 3.17	5.26 ± 2.08	57.94 ± 28.64	57.49 ± 31.56	45.53 ± 12.65	31.43 ± 8.99
>20.5 rotten	1.35 ± 1.35	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Palms	1.41 ± 1.01	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00	0.00 ± 0.00
Total wood	25.39 ± 4.07	8.52 ± 1.98	103.56 ± 35.10	94.18 ± 35.22	53.06 ± 12.34	37.89 ± 8.96
Total	53.31 ± 4.84	8.78 ± 1.98	119.24 ± 35.02	94.74 ± 35.18	72.67 ± 73.05	38.24 ± 8.96
Ash		4.78 ± 0.56		2.05 ± 0.17		3.00 ± 0.28

Table 2. General weather conditions, moisture content of selected fuels (mean ± SE), and range in flame length during fires in cattle pastures converted from tropical moist forest, Para and Rondonia, Brazil.

	Francisco, Para	Durval, Rondonia	Joao, Rondonia
Date of burn	9 September 1991	25 September 1992	31 August 1992
Temperature (°C)	34	30	32
Relative humidity (%)	38	46	55
Wind speed (kph)	1-8	0-6	0-8
Moisture content (%)			
Soil surface	2.0 ± 0.5	--	17.8 ± 2.5
Dicots	--	--	181.5 ± 17.0
Wood >7.6 cm diam	7.5 ± 2.0	--	8.2 ± 1.0
Litter/dead grass	6.0 ± 0.5	--	2.7 ± 0.7
Live grass	209.1 ± 11.5	--	225.0 ± 16.7
Flame length (m)	0.5-4	1-4	3-4

-- No data

Table 3. Mean nutrient concentrations of aboveground biomass in Amazonian cattle pastures. Numbers are mean $\pm$ standard error of all samples combined from pasture sites in Para and Rondonia, Brazil.

Component	Carbon (%)	Nitrogen (mg g^{-1})	Sulphur (mg g^{-1})	Phosphorus (mg g^{-1})	Potassium (mg g^{-1})	Calcium (mg g^{-1})
Litter/dead grass	45.40 $\pm$ 0.75	8.48 $\pm$ 2.02	1.10 $\pm$ 0.10	0.63 $\pm$ 0.17	3.75 $\pm$ 1.12	3.22 $\pm$ 0.08
Grass-prefire	45.91 $\pm$ 0.67	13.06 $\pm$ 1.02	1.43 $\pm$ 0.15	1.11 $\pm$ 0.22	15.81 $\pm$ 4.49	1.70 $\pm$ 0.25
Grass-postfire	46.60 $\pm$ 0.04	7.01 $\pm$ 0.37	1.25 $\pm$ 0.07	0.78 $\pm$ 0.02	15.59 $\pm$ 0.98	0.90 $\pm$ 0.06
Dicots-prefire	49.65 $\pm$ 0.72	14.85 $\pm$ 2.35	2.04 $\pm$ 0.23	1.13 $\pm$ 0.35	10.60 $\pm$ 0.50	4.79 $\pm$ 0.51
Dicots-postfire	49.16 $\pm$ 0.21	7.54 $\pm$ 0.94	1.30 $\pm$ 0.10	1.25 $\pm$ 0.10	8.35 $\pm$ 0.89	6.13 $\pm$ 0.47
Wood debris (cm diam)						
0-0.64	49.17 $\pm$ 0.30	7.71 $\pm$ 0.20	0.83 $\pm$ 0.17	0.63 $\pm$ 0.34	4.51 $\pm$ 1.60	4.53 $\pm$ 0.48
0.65-2.54	49.71 $\pm$ 0.22	5.25 $\pm$ 0.70	0.53 $\pm$ 0.03	0.33 $\pm$ 0.09	3.28 $\pm$ 0.51	2.62 $\pm$ 0.57
2.55-7.6	50.00 $\pm$ 0.16	3.88 $\pm$ 0.96	0.41 $\pm$ 0.21	0.19 $\pm$ 0.07	1.65 $\pm$ 0.78	1.27 $\pm$ 0.70
>7.6 sound	50.69 $\pm$ 0.30	3.82 $\pm$ 0.34	0.47 $\pm$ 0.05	0.19 $\pm$ 0.10	0.82 $\pm$ 0.44	1.29 $\pm$ 0.75
>7.6 rotten	49.07 $\pm$ 0.70	5.93 $\pm$ 0.44	0.58 $\pm$ 0.07	0.12 $\pm$ 0.01	0.77 $\pm$ 0.11	1.47 $\pm$ 0.39
Palms	47.96 $\pm$ 0.02	6.87 $\pm$ 0.94	1.02 $\pm$ 0.09	1.04 $\pm$ 0.08	15.42 $\pm$ 0.47	1.15 $\pm$ 0.10

Table 4. Nutrient concentration of ash following fires in cattle pastures of Para and Rondonia, Brazil. Numbers are mean and standard error.

Component	Francisco, Para	Durval, Rondonia	Joao, Rondonia
Nitrogen (mg g^{-1})	4.22 ± 0.63	8.85 ± 1.08	4.7 ± 0.69
Carbon (%)	17.48 ± 2.20	25.35 ± 1.60	20.73 ± 1.59
Sulphur (mg g^{-1})	6.30 ± 1.29	3.17 ± 0.11	3.69 ± 0.41
Phosphorus (mg g^{-1})	6.11 ± 0.86	2.45 ± 0.14	3.79 ± 0.24
Potassium (mg g^{-1})	68.40 ± 10.48	34.01 ± 1.22	33.42 ± 6.82
Calcium (mg g^{-1})	48.96 ± 6.03	16.80 ± 2.22	20.65 ± 3.84
Organic matter (%)	nd[*]	35.78 ± 2.30	28.55 ± 3.12

[*] nd = no data

Table 5. Dynamics of aboveground nutrient pools before and after burning cattle pastures in Para and Rondonia, Brazil. Numbers are mean ± standard error.

	Francisco, Para	Durval, Rondonia	Joao, Rondonia
NITROGEN (kg ha^{-1})			
Total pool-prefire	304 ± 41[a]	661 ± 145[b]	374 ± 57[a]
% of TAGB	0.57	0.55	0.51
Residual fuels-postfire	32 ± 7[a]	404 ± 15[b]	155 ± 36[c]
Release from biomass	272 ± 42[a]	257 ± 50[a]	220 ± 29[a]
Ash	11 ± 1[a]	18 ± 1[b]	14 ± 1[c]
Residual + ash	43 ± 7[a]	420 ± 14[b]	169 ± 35[c]
Site loss	261 ± 42[a]	240 ± 50	205 ± 29[ab]
CARBON (Mg ha^{-1})			
Total pool-prefire	26 ± 2[a]	59 ± 18[a]	36 ± 7[b]
% of TAGB	48.77	49.48	49.54
Residual fuels-postfire	4 ± 1[a]	48 ± 18	19 ± 5[c]
Release from biomass	21 ± 2[a]	12 ± 5[b]	16 ± 3[ab]
Ash	0.8 ± 0.1[a]	0.5 ± 0[b]	0.6 ± 0.0[b]
Residual + ash	5 ± 1[a]	48 ± 18[b]	20 ± 5[b]
Site loss	21 ± 2[a]	11 ± 5[b]	16 ± 3[ab]
SULPHUR (kg ha^{-1})			
Total pool-prefire	48 ± 5[a]	78 ± 14[b]	42 ± 6[a]
% of TAGB	0.09	0.06	0.06
Residual fuels-postfire	5 ± 1[a]	53 ± 19[b]	14 ± 3[a]
Release from biomass	43 ± 5[a]	25 ± 6[b]	27 ± 3[b]
Ash	18 ± 2[a]	6 ± 0[c]	11 ± 1[b]
Residual + ash	22 ± 2[a]	59 ± 20[b]	25 ± 3[a]
Site loss	25 ± 5[a]	19 ± 6[a]	16 ± 3[a]

* Different superscripted lower case letters denote a significant difference among cattle pastures.

Table 5 (Continued). Dynamics of aboveground nutrient pools before and after burning cattle pastures in Para and Rondonia, Brazil. Numbers are mean ± standard error.

	Francisco, Para	Durval, Rondonia	Joao, Rondonia
	PHOSPHORUS (kg ha^{-1})		
Total pool-prefire	30 ± 5[a]	23 ± 5[a]	11 ± 1[b]
% of TAGB	0.06	0.02	0.02
Residual fuels-postfire	2 ± 0[a]	11 ± 2[b]	1 ± 0.2[a]
Release from biomass	28 ± 5[a]	10 ± 2[b]	10 ± 1[b]
Ash	17 ± 2[a]	5 ± 0[c]	10 ± 0.4[b]
Residual + ash	19 ± 2[a]	16 ± 2[b]	11 ± 0.5[c]
Site loss	11 ± 5[a]	5 ± 2[a]	0.1 ± 1.1[a]
	POTASSIUM (kg ha^{-1})		
Total pool-prefire	221 ± 11[a]	152 ± 18[a]	122 ± 15[a]
% of TAGB	0.41	0.13	0.17
Residual fuels-postfire	18 ± 4[a]	55 ± 11[b]	11 ± 2[a]
Release from biomass	203 ± 42[a]	97 ± 12[b]	111 ± 13[b]
Ash	192 ± 23[a]	70 ± 4[b]	89 ± 4[b]
Residual + ash	210 ± 23[a]	125 ± 12[b]	101 ± 4[b]
Site loss	11 ± 46[a]	33 ± 14	21 ± 14[b]
	CALCIUM (kg ha^{-1})		
Total pool-prefire	162 ± 15[a]	108 ± 84[b]	84 ± 9[b]
% of TAGB	0.30	0.09	0.12
Residual fuels-postfire	25 ± 6[a]	49 ± 10[b]	19 ± 4[a]
Release from biomass	137 ± 14[a]	47 ± 7[b]	65 ± 6
Ash	137 ± 16[a]	34 ± 2[b]	55 ± 2[b]
Residual + ash	162 ± 17[a]	93 ± 23[b]	74 ± 5[b]
Site loss	0 ± 0[a]	16 ± 8[b]	10 ± 6[b]

* Different superscripted letters denote a significant difference among cattle pastures.

Table 6. Soil nutrient concentration in cattle pastures of Para and Rondonia, Brazil. Numbers are mean and standard error.

	Francisco, Para		Durval, Rondonia	Joao, Rondonia
Depth (cm)	Prefire	Postfire	Prefire	Prefire
NITROGEN (mg g^{-1})				
0-2.5	2.57 ± 0.12	2.93 ± 0.17	3.70 ± 0.82	2.86 ± 0.49
2.5-10	1.75 ± 0.13	1.76 ± 0.02	2.58 ± 0.60	1.67 ± 0.10
CARBON (%)				
0-2.5	3.55 ± 0.12	4.22 ± 0.30	5.78 ± 1.58	3.76 ± 0.60
2.5-10	2.45 ± 0.10	2.25 ± 0.11	3.50 ± 0.87	2.11 ± 0.17
SULPHUR (mg g^{-1})				
0-2.5			0.31 ± 0.05	0.23 ± 0.01
2.5-10			0.25 ± 0.02	0.23 ± 0.01
PHOSPHORUS (mg g^{-1})				
0-2.5			0.23 ± 0.05	0.19 ± 0.02
2.5-10			0.13 ± 0.01	0.11 ± 0.00
POTASSIUM (mg g^{-1})				
0-2.5			0.18 ± 0.04	0.37 ± 0.03
2.5-10			0.09 ± 0.02	0.08 ± 0.02
CALCIUM (mg g^{-1})				
0-2.5			0.42 ± 0.18	0.72 ± 0.05
2.5-10			0.25 ± 0.09	0.21 ± 0.06

Table 7. Soil nutrient mass in cattle pastures of Para and Rondonia, Brazil. Numbers are mean and standard error.

Depth (cm)	Francisco, Para		Durval, Rondonia	Joao, Rondonia
	Prefire	Postfire	Prefire	Prefire
NITROGEN (kg ha^{-1})				
0-2.5	860 ± 20	980 ± 23	1182 ± 65	914 ± 50
2.5-10	1734 ± 74	1748 ± 75	2477 ± 137	1599 ± 88
CARBON (Mg ha^{-1})				
0-2.5	11.9 ± 0.4	14.1 ± 1.0	18.5 ± 1.0	12.0 ± 0.7
2.5-10	24.3 ± 1.0	22.3 ± 1.1	33.6 ± 1.9	20.2 ± 1.1
SULPHUR (kg ha^{-1})				
0-2.5			99.7 ± 5.5	75.0 ± 4.1
2.5-10			244.0 ± 13.9	223.5 ± 12.3
PHOSPHORUS (kg ha^{-1})				
0-2.5			63.9 ± 3.5	59.9 ± 3.3
2.5-10			124.6 ± 6.9	105.4 ± 5.8
POTASSIUM (kg ha^{-1})				
0-2.5			44.7 ± 2.5	117.4 ± 6.5
2.5-10			86.3 ± 4.8	76.7 ± 4.2
CALCIUM (kg ha^{-1})				
0-2.5			105.4 ± 5.8	230.0 ± 12.7
2.5-10			239.6 ± 13.2	201.3 ± 11.1

Figure 1A-1F. Nutrient pools of cattle pastures before and after fires in Para and Rondonia, Brazil. The vertical lines represent one standard error of the total nutrient pools. Litter is signified by ▨ , live grass by ▨ , dicots by ▨ , wood debris 0-0.64 by ▨ , 0.65-2.54 by ▨ , 2.55-7.6 by ▤ , 7.6-20.5 by ☐ , >20.5 by ▨ , palms by ■ , and ash by ▤ .
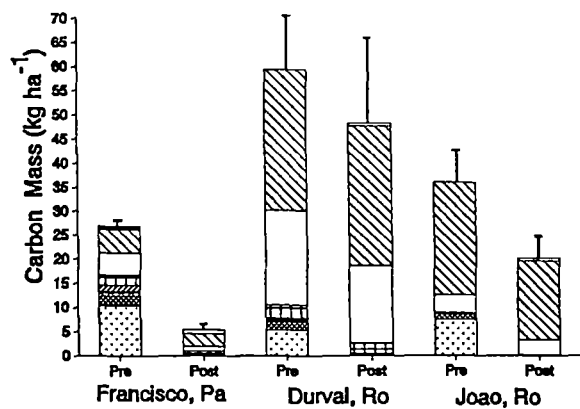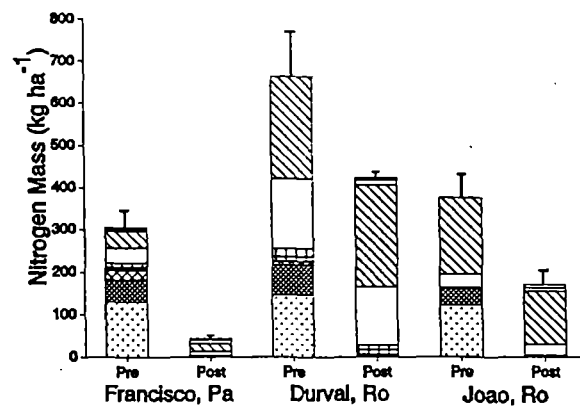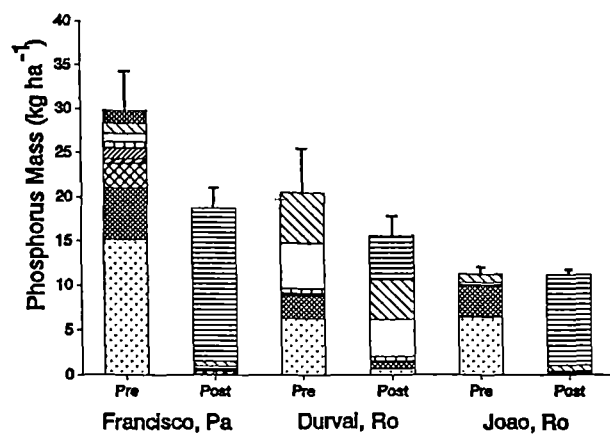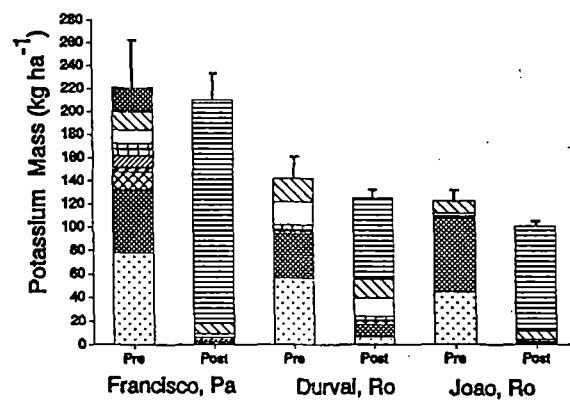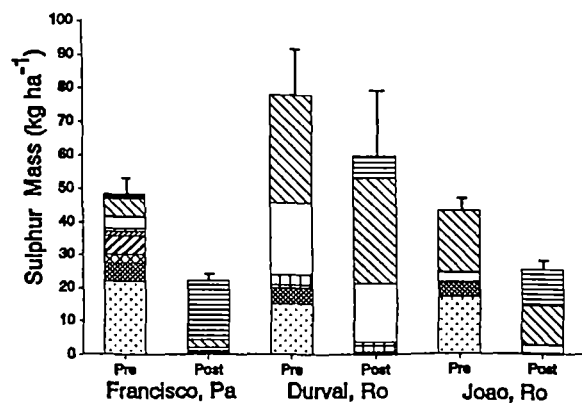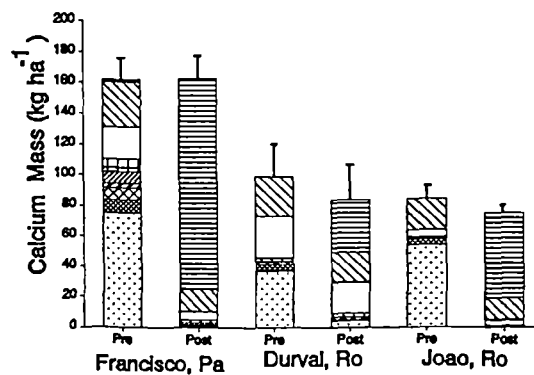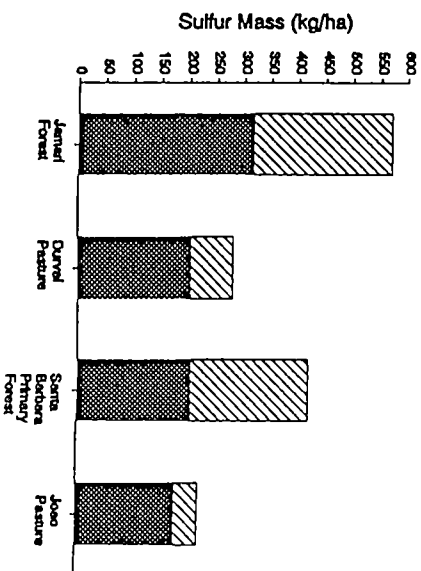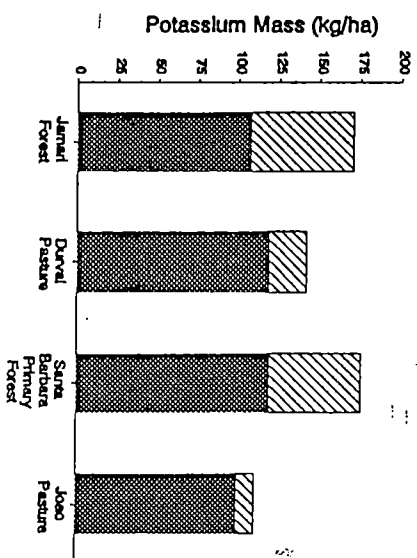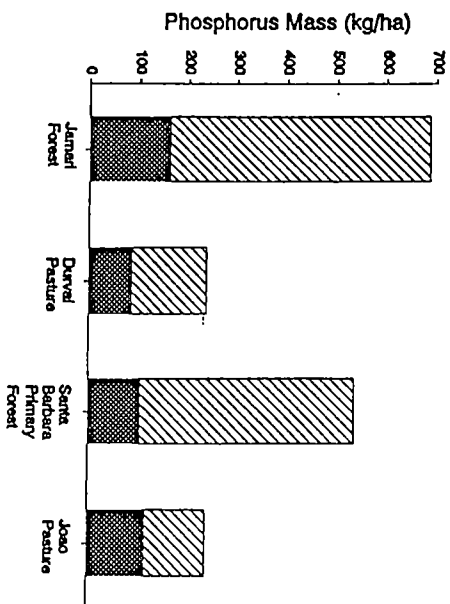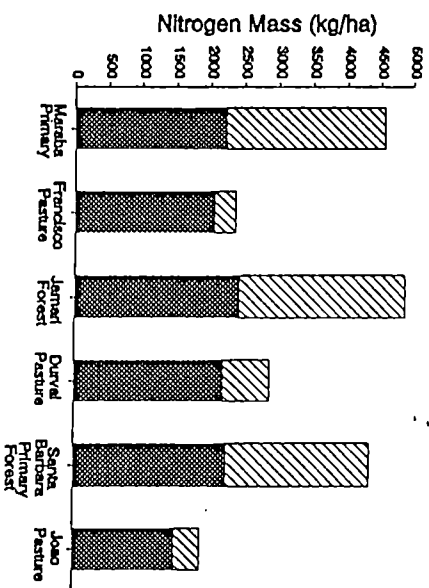
Figure 2. Ecosystem pools of primary forests and cattle pastures. These nutrient pools are comprised of the total aboveground mass ▨ and surface soils ▨ . Soil nutrient pools are representative of equivalent amounts of soil mass in both primary forests and pastures. This is the equivalent mass found in the top 10 cm of soils in primary forests. As soil bulk density is higher in pastures, pools reported in this figure are lower than those of Table 7.

Sulfur Mass (kg/ha)

Jamari Forest
Durval Pasture
Santa Barbara Primary Forest
Joao Pasture

Phosphorus Mass (kg/ha)

Jamari Forest
Durval Pasture
Santa Barbara Primary Forest
Joao Pasture

Carbon Mass (kg/ha)

Maraba Primary
Francisco Pasture
Jamari Forest
Durval Pasture
Santa Barbara Primary Forest
Joao Pasture

Calcium Mass (kg/ha)

Jamari Forest
Durval Pasture
Santa Barbara Primary Forest
Joao Pasture

Potassium Mass (kg/ha)

Jamari Forest
Durval Pasture
Santa Barbara Primary Forest
Joao Pasture

Nitrogen Mass (kg/ha)

Maraba Primary
Francisco Pasture
Jamari Forest
Durval Pasture
Santa Barbara Primary Forest
Joao Pasture